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MECHANICAL PROPERTIES OF NEAT POLYMER
MATRIX MATERIALS AND THEIR UNIDIRECTIONAL
CARBON FIBER-REINFORCED COMPOSITES

Richard S. Zimmerman and Donald F. Adams

UNIVERSITY OF WYOMING
Laramie, Wyoming

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National Aeronautics and
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Langley Research Center
Hampton, Virginia 23665

Preface

This technical report presents the results of the third twelve-month effort on NASA-Langley Research Grant NAG-1-277. The NASA-Langley Technical Monitor is Dr. Norman J. Johnston of the Materials Division.

Only the experimental results of this program will be presented here; all analytical results will be documented in a subsequent report. All work was performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming. Co-Principal Investigators were Mr. Richard S. Zimmerman, Staff Engineer, and Dr. Donald F. Adams, Professor.

Making major contributions to the program were Eric Q. Lewis, William M. Pressnall, Mathew W. Graf, David B. Scholz, and Douglas L. McLarty, undergraduate student members of the Composite Materials Research Group.

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SECTION 1

SUMMARY

This continuing study involves the investigation of unreinforced (neat) resin properties and their relations to composite material behavior. This third-year effort, following the first two studies in which only neat resins were tested, [1,2], included carbon fiber-reinforced composites testing as well. Two neat resin systems were chosen here for detailed mechanical property characterization. CYCOM 907 epoxy, which was tested last year, was tested at one additional condition to add to its data base. Also, four carbon fiber-reinforced unidirectional composite materials incorporating previously studied neat resin systems were chosen for mechanical property characterization.

The two neat epoxy resin systems were American Cyanamid CYCOM 1806 and Union Carbide ERX-4901B, an epoxy cured with metaphenylene diamine (MPDA). The four unidirectional carbon fiber composite systems chosen were AS4/3502, AS6/5245-C, T300/BP907, and C6000/1806. The properties of the resin systems contained in these composites were determined during the three years of this study.

The CYCOM 1806 epoxy is a candidate material for use in aerospace applications, while the ERX-4901B(MPDA) is a second version of the epoxy studied during the second year of this grant. Both resin systems were supplied in uncured bulk form by NASA-Langley, and were cast into various shapes as required to prepare test specimens for use in this study. Resin casting was performed using the same techniques developed previously by the CMRG. These processes are discussed in detail in the first-year report [1].

1.1 Neat Resin Properties

Extensive mechanical characterization was completed on the two neat resin systems, at six different environmental conditions. Dry and moisture-saturated specimens were tested at 23°C, 82°C, and 121°C. Testing performed during the present study included tensile, torsional shear, single-edge notched-bend (SEN) fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion tests. This group of tests was performed to allow a comparison of material properties for all resin systems studied. The CYCOM 907 epoxy was tested at -80°C, dry in tension and Iosipescu shear for use by NASA-Langley in a special study.

The CYCOM 1806 epoxy neat resin is comparable to the Hercules 3502 epoxy neat resin, the baseline resin system of the first-year study. The ERX-4901B(MPDA) epoxy neat resin is comparable to the ERX-4901A(MDA) epoxy version of the second-year study.

Tables 1 through 6 are repeated from Reference [2], with the two additional neat resins property averages added for each of the six environmental conditions. These tables thus provide a complete record of all material properties for the ten neat resins tested to date. The reader can compare resin systems at a glance for any of the six environmental conditions.

The Union Carbide ERX-4901B(MPDA) degraded rapidly after moisture saturation, which prevented measuring tensile properties above 60°C and shear properties above 82°C. Table 5 therefore includes no tensile properties and Table 6 no tensile or shear properties for the ERX-4901B (MPDA) epoxy at these test conditions.

TABLE 1

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
ROOM TEMPERATURE, DRY CONDITION*

Neat Resin System	Tensile Strength (MPa)	Tensile Strength (ksi)	Shear Strength (MPa)	Shear Strength (ksi)	Young's Modulus (GPa)	Young's Modulus (Msi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Poisson's Ratio	Ult. Tensile Strain (percent)	Ult. Shear Strain (percent)	Coefficient of Thermal Expansion (10^{-6}/°C)
3502	41	6.0	60	8.7	3.8	0.55	1.8	0.26	0.36	1.0	3.6	50.5
914	28	4.0	80	11.6	4.0	0.58	1.5	0.22	0.36	0.7	5.9	58.4
2220-1	43	6.3	77	11.1	3.0	0.43	1.5	0.22	0.36	1.4	6.2	55.6
2220-3	46	6.7	68	9.9	3.0	0.44	1.4	0.20	0.36	1.5	6.5	53.6
HX-1504	77	11.2	98	14.2	3.9	0.57	1.8	0.26	0.37	2.0	8.1	50.8
5245-C	74	10.7	56	8.1	3.7	0.54	1.0	0.14	0.39	2.1	5.9	48.0
BP907	86	12.5	41	5.9	3.2	0.47	1.2	0.17	0.42	3.7	3.3	54.8
4901A (MDA)	109	15.8	123	17.8	4.8	0.70	2.0	0.29	0.41	2.1	8.0	57.8
1806	88	12.8	93	13.4	3.1	0.44	1.2	0.18	0.39	3.2	17.1	58.2
4901B (MPDA)	**97**	**14.1**	**127**	**18.4**	**5.6**	**0.81**	**2.2**	**0.32**	**0.33**	**1.7**	**5.3**	**61.6**

*The properties for the first eight resin systems are repeated from Reference [2].

TABLE 2

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
82°C, DRY CONDITION*

Neat Resin System	Tensile Strength (MPa)	Tensile Strength (ksi)	Shear Strength (MPa)	Shear Strength (ksi)	Young's Modulus (GPa)	Young's Modulus (Msi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Ult. Tensile Strain (percent)	Ult. Shear Strain (percent)	Poisson's Ratio
3502	42	6.1	70	10.2	3.1	0.45	1.6	0.23	1.6	5.5	0.37
914	32	4.6	75	10.9	3.2	0.46	1.4	0.20	1.2	6.1	0.37
2220-1	73	10.6	74	10.8	2.6	0.38	1.2	0.17	2.1	14.5	0.36
2220-3	70	10.2	66	9.6	2.5	0.36	1.1	0.16	2.4	12.8	0.35
HX-1504	71	10.3	77	11.1	3.3	0.48	1.5	0.22	2.4	11.0	0.36
5245-C	62	9.0	66	9.6	3.4	0.50	1.4	0.21	2.1	5.9	0.40
BP907	67	9.7	46	6.7	2.8	0.40	1.0	0.14	5.4	>6.0	0.42
4901A(MDA)	57	8.2	74	10.8	2.8	0.41	1.4	0.21	8.2	7.5	0.44
1806	76	10.9	65	9.5	2.5	0.36	1.0	0.14	5.0	15.0	0.46
4901B(MPDA)	73	10.5	95	13.8	3.9	0.56	2.1	0.30	2.6	5.0	0.41

*The properties for the first eight resin systems are repeated from Reference [2].

TABLE 3

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
121°C, DRY CONDITION*

Neat Resin System	Tensile Strength (MPa)	Tensile Strength (ksi)	Shear Strength (MPa)	Shear Strength (ksi)	Young's Modulus (GPa)	Young's Modulus (Msi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Poisson's Ratio	Ult. Tensile Strain (percent)	Ult. Shear Strain (percent)
3502	54	7.8	**		2.8	0.40	**		0.46	1.9	**
914	19	2.8	**		0.7	0.10	**		0.44	6.9	**
2220-1	60	8.7	**		2.2	0.32	**		0.42	4.3	**
2220-3	62	9.0	**		2.1	0.31	**		0.39	4.8	**
HX-1504	62	9.0	54	7.8	2.7	0.39	1.1	0.16	0.37	3.5	11.7
5245-C	76	11.0	67	9.7	3.1	0.45	1.0	0.15	0.40	5.0	7.6
BP907	1	0.1	1	0.1	2.6	0.38	1.4	0.20	0.41	8.2	>6.0
4901A (MDA)	10	1.4	32	4.6	0.5	0.07	1.0	0.15	0.35	8.2	6.0
1806	63	9.1	46	6.7	2.4	0.35	0.9	0.13	0.44	4.8	15.7
4901B (MPDA)	10	1.4	24	3.5	0.1	0.02	0.5	0.07	0.45	15.2	14.3

*The properties for the first eight resin systems are repeated from Reference [2].
**Property not measured at this environmental condition

TABLE 4

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
ROOM TEMPERATURE, MOISTURE-SATURATED CONDITION*

Neat Resin System	Tensile Strength (MPa)	(ksi)	Shear Strength (MPa)	(ksi)	Young's Modulus (GPa)	(Msi)	Shear Modulus (GPa)	(Msi)	Poisson's Ratio	Ult. Tensile Strain (%)	Ult. Shear Strain (%)	Coefficient of Thermal Expansion (10^{-6}/°C)	Coefficient of Moisture Expansion (10^{-3}/%M)	Equilibrium Moisture Content(%M)
3502	36	5.2	50	7.2	3.5	0.51	1.6	0.23	0.43	1.2	3.3	55.5	2.70	5.0
914	48	7.0	69	10.0	3.1	0.45	1.4	0.21	0.43	1.7	6.3	62.6	3.02	7.0
2220-1	68	9.9	68	9.9	3.1	0.45	1.5	0.22	0.41	2.8	6.7	58.6	2.51	3.8
2220-3	67	9.7	68	9.9	3.1	0.45	1.5	0.22	0.43	3.3	13.1	57.5	2.96	4.0
HX-1504	51	7.4	66	9.6	3.5	0.51	1.5	0.22	0.40	1.6	5.8	54.7	2.07	3.8
5245-C	47	6.8	68	9.8	4.0	0.58	1.4	0.20	0.39	1.6	4.9	50.2	1.52	2.1
BP907	59	8.4	44	6.4	2.9	0.42	1.1	0.16	0.43	2.6	5.6	58.0	2.29	5.1
4901A (MDA)	79	11.5	74	10.7	3.6	0.52	1.7	0.24	0.40	4.6	7.7	60.9	1.55	7.2
1806	78	11.2	73	10.6	3.0	0.44	1.1	0.15	0.46	5.1	14.1	63.2	2.53	2.9
4901B (MPDA)	9	1.3	46	6.7	0.8	0.11	1.3	0.18	0.48	0.8	3.3	94.1	1.00	10.2

*The properties for the first eight resin systems are repeated from Reference [2].

TABLE 5

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
82°C, MOISTURE-SATURATED CONDITION*

Neat Resin System	Tensile Strength (MPa)	Tensile Strength (ksi)	Shear Strength (MPa)	Shear Strength (ksi)	Young's Modulus (GPa)	Young's Modulus (Msi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Poisson's Ratio	Ult. Tensile Strain (percent)	Ult. Shear Strain (percent)
3502	25	3.6	46	6.6	2.6	0.37	1.0	0.14	0.42	1.0	4.5
914	32	4.6	39	5.6	2.1	0.31	1.2	0.17	0.40	1.6	4.5
2220-1	46	6.7	55	8.0	2.1	0.30	1.2	0.18	0.43	3.7	9.5
2220-3	44	6.4	50	7.2	2.1	0.31	1.3	0.19	0.47	4.8	12.8
HX-1504	48	6.9	62	9.0	2.8	0.40	1.0	0.15	0.41	2.0	8.8
5245-C	57	8.2	65	9.4	3.1	0.45	1.4	0.10	0.42	3.9	5.8
BP907	2	0.3	5	0.7	0.1	0.01	0.2	0.03	0.43	8.2	>6.0
4901A(MDA)	3	0.4	5	0.7	0.1	0.01	0.1	0.02	0.42	7.9	11.5
1806	36	5.2	45	6.5	1.7	0.24	0.7	0.10	0.44	10.5	20.7
4901B(MPDA)	**	**	2	0.3	**	**	0.1	0.01	**	**	14.8

*The properties for the first eight resin systems are repeated from Reference [2].
**Property not measured at the environmental condition

TABLE 6

AVERAGE MATERIAL PROPERTIES FOR TEN NEAT RESIN SYSTEMS;
121°C, MOISTURE-SATURATED CONDITION*

Neat Resin System	Tensile Strength (MPa)	Tensile Strength (ksi)	Shear Strength (MPa)	Shear Strength (ksi)	Young's Modulus (GPa)	Young's Modulus (Msi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Poisson's Ratio	Ult. Tensile Strain (percent)	Ult. Shear Strain (percent)
3502	15	2.2	**		1.9	0.28	**		0.45	0.9	**
914	8	1.2	**		0.3	0.04	**		0.49	7.0	**
2220-1	23	3.4	**		1.0	0.15	**		0.49	5.2	**
2220-3	21	3.0	**		0.9	0.13	**		0.49	7.5	**
HX-1504	16	2.3	37	5.4	0.9	0.13	6.8	0.98	0.49	7.9	7.9
5245-C	28	4.0	34	4.9	0.9	0.13	0.9	0.13	0.49	8.2	14.1
BP907 ***											
4901A(MDA) ***											
1806	11	1.7	23	3.4	0.3	0.05	0.2	0.03	0.38	13.4	13.0
4901B(MPDA) ***											

*The properties for the first eight resin systems are repeated from Reference [2].
**Property not measured at this environmental condition.
***Material not tested due to highly degraded properties at this environmental condition.

Coefficient of thermal expansion (CTE) testing was performed on both dry and moisture-saturated specimens. CTE's were measured over the temperature range from 40°C to 121°C, using a computer-controlled quartz glass tube dilatometer and LVDT. The CYCOM 1806 neat epoxy behaved quite linearly over the temperature range, while the ERX-4901B(MPDA) was highly nonlinear over the temperature range. Both epoxies displayed higher CTE values after being moisture-saturated, as expected.

Coefficient of moisture expansion (CME) testing was performed on the two neat epoxy resin systems, from dry to saturation at 65°C. Moisture saturation levels were also measured, the CYCOM 1806 equilibrium value being 2.9 percent by weight and the ERX-4901B(MPDA) 10.2 percent by weight.

The CYCOM 1806 epoxy performed as well as the Hercules 3502 baseline epoxy at most conditions, and exhibited better strengths at the lower temperature conditions than the 3502 system. The CYCOM 1806 did not retain stiffness and strength at the elevated temperature, wet conditions as well as the 3502 system, however. The CYCOM 1806 epoxy displayed slightly lower tensile and shear moduli at all conditions compared to the 3502 epoxy.

The ERX-4901B(MPDA) epoxy was very similar to the ERX-4901A(MDA) epoxy tested in the second year. Tensile and shear properties were only slightly higher for the ERX-4901B(MPDA) in the dry condition at the lower temperatures. The ERX-4901B(MPDA) did degrade to a greater degree when exposed to high test temperatures in the moisture-saturated condition than did the ERX-4901A(MDA) version of the Union Carbide epoxy.

The two neat resins tested failed to satisfy the isotropic relation between E, ν, and G, just as observed in the first two studies [1,2].

Why these bulk polymers do not respond to mechanical loadings in an isotropic manner has yet to be explained.

Single-edge notched-bend (SEN) fracture toughness testing was also performed on the two neat resin systems. Improvements in the technique used in performing this test resulted in more reasonable values than in the previous testing [1,2]. Both resin systems exhibited relatively low Mode I Critical Energy Release Rates (G_{IC}). Average Mode I Strain Energy Release Rates are given in Table 7.

Scanning electron microscopy (SEM) was performed on selected failed test specimens. These SEM photographs add to the large collection of neat resin failure surfaces accumulated in References [1,2].

As stated earlier, only experimental results are presented in this report. All analytical predictions and correlations of composite properties will be published in a subsequent report.

Specimen fabrication and test methods are presented in Section 3. All experimental results are presented in detail in Sections 4 and 5 of this report. Scanning electron microscope observations are included in Section 6, and conclusions in Section 7. Appendix A contains tables of individual test specimen results for all tests. Individual stress-strain curves are presented in Appendix B.

1.2 Unidirectional Composite Properties

Table 8 shows the average material properties for the four carbon fiber-reinforced composite materials tested. Most of the composite testing was conducted at the 23°C and 100°C dry conditions indicated in Table 8. Additional transverse tension testing was performed at 120°C since this test yields important strength and stiffness information

TABLE 7

AVERAGE FRACTURE TOUGHNESS VALUES FOR THREE NEAT RESIN SYSTEMS

Neat Resin System	Test Temperature (°C)	Mode I Strain Energy Release Rate, Dry (J/m^2)	Dry ($in\text{-}lb/in^2$)	Moisture-Saturated (J/m^2)	Moisture-Saturated ($in\text{-}lb/in^2$)
CYCOM 1806	23	116	0.7	296	1.7
	82	375	2.1	148	0.9
	121	105	0.6	111	0.6
ERX-4901B(MPDA)	23	191	1.1	50	0.3
	82	83	0.5	4	<0.1
BP907 [2]	-80	293	1.7	--	--
	23	1293	7.4	2840	16.2
	82	3286	18.8	45062	257.3

TABLE 8

AVERAGE PROPERTIES OF THE FOUR CARBON FIBER, POLYMER MATRIX UNIDIRECTIONAL COMPOSITE MATERIALS TESTED

Material System	Test Temp. (°C)	Axial Tensile Strength (ksi)	(MPa)	Axial Tensile Modulus (Msi)	(GPa)	Ultimate Axial Tensile Strain (percent)	Poisson's Ratio	Transverse Tensile Strength (ksi)	(MPa)	Transverse Tensile Modulus (Msi)	(GPa)
AS4/3502	23	264	1820	18.9	130	1.2	0.35	9.3	64	1.4	9.7
	100	300	2069	19.5	134	1.3	0.34	7.2	50	1.2	8.3
	121	--	--	--	--	--	--	6.4	44	1.3	9.0
AS6/5245-C	23	370	2551	19.1	132	1.6	0.34	8.0	55	1.3	9.0
	100	359	2475	22.0	152	1.6	0.32	6.8	47	1.2	8.3
	121	--	--	--	--	--	--	8.5	59	1.2	8.3
T300/BP907	23	207	1427	18.1	125	1.0	0.34	12.7	88	1.1	7.6
	100	185	1276	16.4	113	1.1	0.44	2.7	19	0.5	3.4
	121	--	--	--	--	--	--	0.8	6	>0.1	>0.7
C6000/1806	23	306	2110	19.2	132	1.4	0.37	9.3	64	1.3	9.0
	100	294	2027	20.1	139	1.4	0.40	10.3	71	1.2	8.3
	121	--	--	--	--	--	--	7.8	54	1.1	7.6

Table 8 (cont.)

Material System	Test Temp. (°C)	Ultimate Transverse Tensile Strain (percent)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
AS/3502	23	0.7	15.6	108	0.86	5.9	5.1
	100	0.6	12.0	83	0.89	6.1	>6.0
	121	0.6	--	--	--	--	--
AS6/5245-C	23	0.6	17.9	123	0.86	5.9	>6.0
	100	0.6	14.4	99	0.72	5.0	>6.0
	121	0.8	--	--	--	--	--
T300/BP907	23	1.1	16.2	112	0.77	5.3	>6.0
	100	1.6	7.9	54	0.22	1.5	>6.0
	121	3.1	--	--	--	--	--
C6000/1806	23	0.8	15.6	108	0.72	5.0	>5.8
	100	1.0	11.3	78	0.67	4.6	>6.0
	121	0.8	--	--	--	--	--

about the matrix material. These are the first composite materials data generated to date in this study. Additional composites testing will be performed in the next-year study.

SECTION 2

Introduction

This report presents the results of the third year of a continuing study of unreinforced (neat) polymer resin materials being considered for various applications in the aerospace industry. The carbon fiber-reinforced composites data also being generated in this program will permit correlations using the micromechanics analysis developed concurrently at the University of Wyoming.

The material properties being generated in this program are providing a much needed data base for fully evaluating these new matrix materials, and composite materials incorporating these neat resins. Ten neat resins and four carbon fiber-reinforced composites have now been characterized in the three years this program has been in progress. New polymer resin systems have been developed during this time, intended to fill needs in the aerospace industry for tough, strong, and stiff matrix materials for use in primary load carrying structures. Some candidates screened to date have been used in aerospace applications, but the large breakthrough desired in toughness has yet to be achieved.

The Composite Materials Research Group (CMRG) at the University of Wyoming has been an active participant in the screening of candidate polymer matrices for a number of years. A process for fabricating neat polymers into test specimens has been developed which has permitted the detailed investigations conducted during the first three years of this grant.

Composites data generated during this third year are now providing the information needed to correlate experimental results

with micromechanics predictions, and thereby verify the numerical model. After the verification process has been completed, considerable time and effort should be saved by restricting preparation and testing of composites to only those attractive candidates identified in the neat resin testing and micromechanics predictions.

SECTION 3

SPECIMEN FABRICATION AND TEST METHODS

3.1 Introduction

An in-depth test program was completed on the two unreinforced (neat) resin systems and four carbon fiber-reinforced composite materials identified in Sections 1 and 2. Some additional work on one previously tested neat resin was also performed. Table 9 shows the neat resin test matrix with the associated environmental conditions; a total of six combinations of temperature and moisture were used for the new

TABLE 9

NEAT RESIN TEST MATRIX

Test Method	Moisture Condition	Test Temperature 23°C	82°C	121°C
Tension	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Shear	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Fracture Toughness	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Coefficient of Thermal Expansion	Dry	3	-40°C to 121°C	
	Moisture-Saturated	3	-40°C to 121°C	
				6 total
Coefficient of Moisture Expansion	98%RH	65°C, Dry to Saturation		
				6 total
		102 Specimens of Each Resin System		

Total for Two Resin Systems: 204 Specimens

neat resin mechanical characterization testing. Table 10 shows the carbon fiber-reinforced composites test matrix; the composite mechanical characterization testing was performed in the dry condition at two temperatures. Neat resin specimens were cast into test configurations from bulk resin. Composite test specimens were cut from unidirectional plates supplied by NASA-Langley. Dry test specimens were stored in dessicators prior to testing while wet test specimens were suspended over distilled water at 74°C in sealed containers until fully moisture saturated. Periodic weighings of these specimens were performed to monitor weight gain versus time, to determine when moisture saturation was achieved.

TABLE 10

CARBON FIBER-REINFORCED UNIDIRECTIONAL COMPOSITE TEST MATRIX

Test Method	Test Temperature* 23°C	Test Temperature* 100°C
Axial Tension	3	3
Transverse Tension	3	3
Iosipescu Shear	3	3
Transverse Coefficient of Thermal Expansion	3	(-40°C to 121°C)
Transverse Coefficient of Moisture Expansion	6	(65°C, Dry to Saturation)
	27 Specimens of Each Composite System	

Total for Four Composite Systems: 108 Specimens

*All testing performed on dry specimens

All static testing was performed using an Instron Model 1125 electromechanical universal testing machine. A BEMCO Model FTU 3.8 environmental chamber was used to maintain the desired elevated test temperatures during testing. A Hewlett-Packard Model 21 MX-E minicomputer was used to record and reduce all test data. A Control Data Corporation CYBER 760 mainframe computer system was used to generate all plots of material properties and groupings of stress-strain plots.

3.2 Cure Cycles for Neat Resins

The three neat resins tested in the current year were cast using the same types of steel molds used during the first two years of this study [1,2]. Recommended cure cycles provided by the resin manufacturers were used to ensure that proper cures were obtained. An initial gel at an intermediate temperature was done in the steel molds before the final cure. The cure cycle for the CYCOM 1806 epoxy included melting the frozen resin at 50-60°C, then stirring at 130°C for 15 minutes to ensure all components of the resin were thoroughly mixed. A degassing step was then performed under 20-24 in. Hg vacuum at 100°C for 15-30 minutes, or until all bubbling and foaming subsided. An initial cure at 135°C for 2 hours was followed by a final cure at 177°C for 3 hours while the specimens were still in the steel molds in an air circulating oven. No free standing cure step was used with the CYCOM 1806 epoxy.

The ERX-4901B(MPDA) was formulated at 50-65°C by mixing 22 grams of 1,3 phenylendiamine (MPDA) catalyst per each 100 grams of bulk epoxy. The mixture was stirred in a beaker under a fume hood until the catalyst crystals were fully dissolved in the epoxy. The mixture was then poured

into molds preheated to 100°C, and the resin degassed at this temperature under 20-24 in. Hg vacuum for 15-20 minutes, or until all bubbling subsided. The seams of all molds were sealed with sealant tape to prevent the liquid resin from running out of the mold. The ERX-4901A(MDA) epoxy, tested in last year's study, also required sealing the mold seams as both versions are quite inviscid at the initial cure temperature. An initial gel at 85°C for 5 hours was followed by an intermediate cure at 120°C for 4 hours. A final cure was performed at 160°C for 10 hours in an air circulating oven after the specimens had been removed from the steel molds.

The CYCOM 907 (also known as BP907) was cured in an identical fashion as in the second year [2] of this grant. The frozen resin was melted in preheated molds at 100°C and subjected to 20-24 in. Hg vacuum for 45-60 minutes before an initial cure for 5 hours at 130°C. A final cure of 3 hours at 177°C was performed in an air circulating oven after the specimens had been removed from the steel molds. The CYCOM 907 was tested at one additional condition, viz., -80°C, dry, for a special NASA-Langley application. Previous testing of this neat resin at six other environmental conditions was completed in the second year of this grant [2].

3.3 Neat Resin Specimen Fabrication

A standard dogbone-shaped specimen was used for all neat resin tensile testing. Specimens were 152 mm (6 in.) long by 5.1 mm (0.2 in.) wide in the gage section, and 2.5 mm (0.1 in.) thick. Each specimen was instrumented with a longitudinal extensometer to measure axial strain and thus generate a complete stress-strain curve. A second

extensometer was used to measure the transverse strain. Poisson's ratio was then calculated using the measured longitudinal and transverse strains. Figure 1 shows the extensometer arrangement used on each neat resin tensile specimen.

A cylindrical dogbone-shaped specimen was used for all neat resin shear testing. Specimens were 152 mm (6 in.) long by 7.4 mm (0.352 in.) in diameter in the gage section and 12.7 mm (0.5 in.) in diameter in the grip section. Each specimen was instrumented with a rotometer to measure angle of twist and thus generate a complete shear stress-shear strain curve. This test specimen and the rotometer were also used in the two previous programs [1,2] and are explained in detail in those reports. Figure 2 shows the typical torsional shear test setup used.

Neat resin fracture toughness testing was performed on the two neat resins using the Single-Edge Notched-Bend (SEN) test method described in ASTM Standard E399 [3]. Test specimens were cast from bulk resin in the same manner as the tensile specimens, being 152 mm (6.0 in.) long, 12.7 mm (0.5 in.) wide, and 6.4 mm (0.25 in.) thick. This thickness was twice the tensile specimen thickness, which allowed the assumption of plane strain in the G_{IC} calculation. Three notches were cut along one edge of each specimen, spaced evenly along the specimen length to allow for three tests of each 15.2 mm (6.0 in.) long rectangular specimen. A water-cooled abrasive blade was used for this notching operation. Figure 3 shows the three-point bend fixture used to test the fracture toughness specimens. Just prior to testing each specimen, a razor blade cooled in liquid nitrogen was used to produce the small crack tip in the

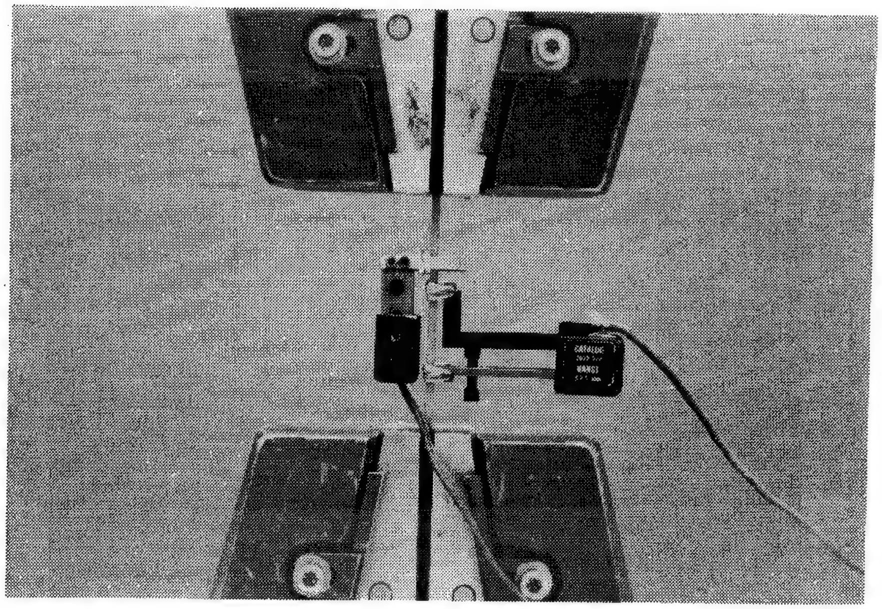

Figure 1. Typical Extensometer Arrangement on a Neat Resin Tension Specimen

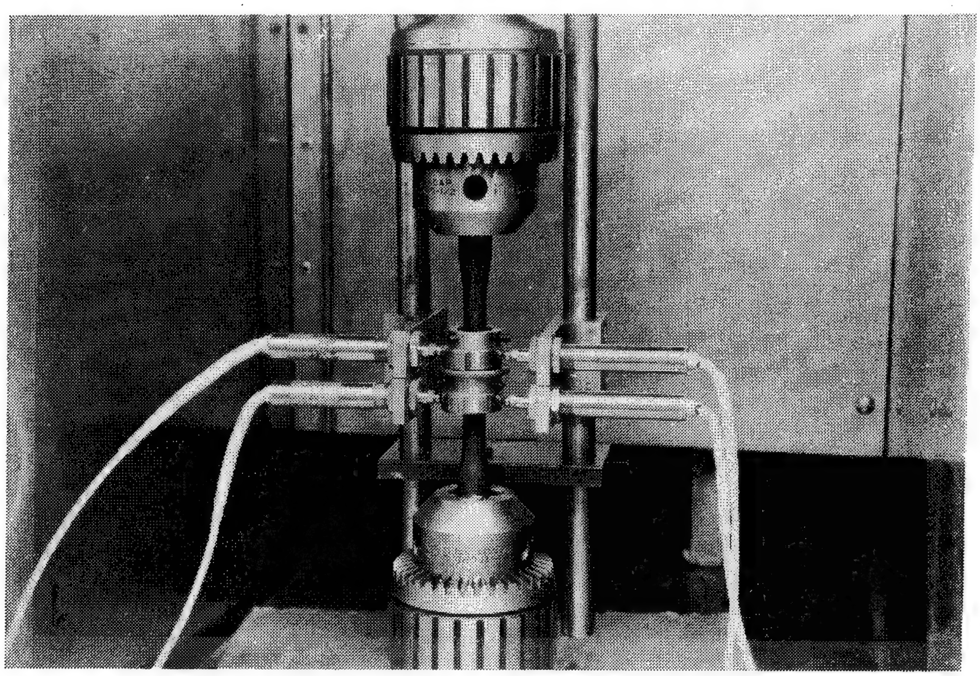

Figure 2. Typical Shear Test Specimen with Rotometer Arrangement for Measuring Angle of Twist.

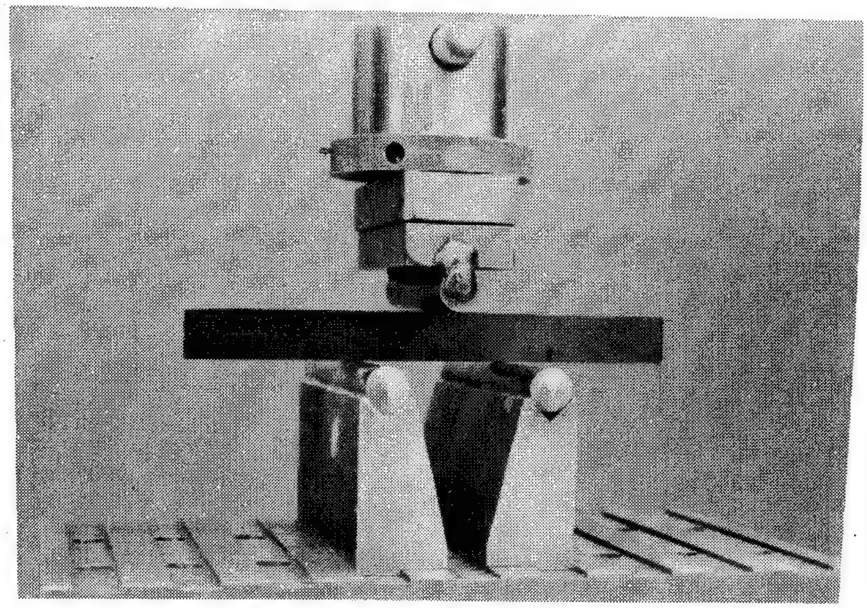

Figure 3. Three Point Bend Fixture Used for Single-Edge Notched-Bend Fracture Toughness Testing.

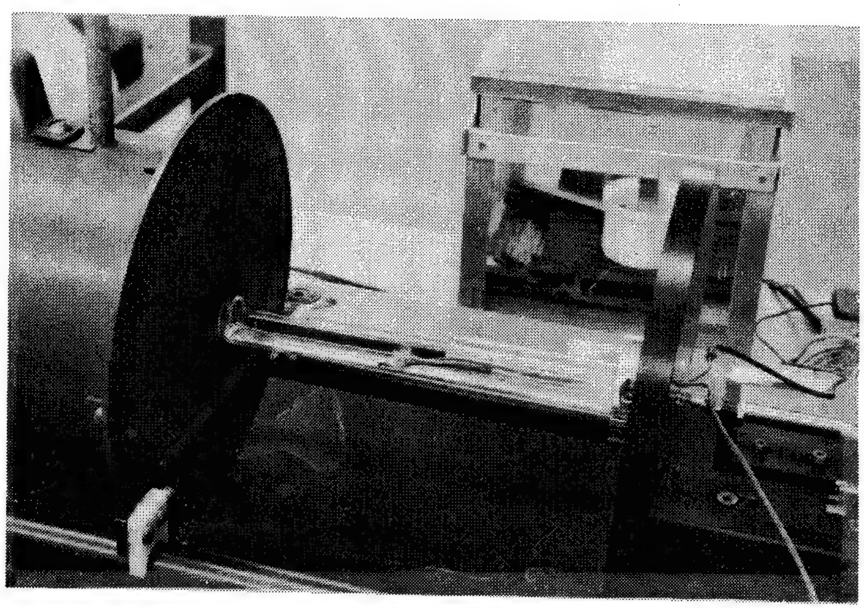

Figure 4. Quartz-Tube Dilatometer Thermal Expansion Apparatus

sawcut notch required for this test to be valid, using a light tap on the razor blade. Some experimentation is required on each resin system to acquire the feel for the proper tapping force on the razor blade. Too hard a tap will result in a broken specimen while too soft a tap will result in an unsatisfactory crack tip and an abnormally high apparent toughness value.

At least three specimens of each neat resin system were used to measure coefficients of thermal expansion (CTE). Specimens were 127 mm (5.0 in.) long by 9.5 mm (0.375 in.) wide. All testing was performed using a microprocessor-controlled quartz-tube dilatometer and an LVDT. Figure 4 shows the CTE test apparatus. Data were acquired on 5¼" floppy disks and later transferred to a CYBER 760 for reduction and plotting. A minimum of two thermal excursions between -40°C and 121°C on both dry and moisture-saturated specimens were performed. A linear regression curve-fit was performed on the length change versus temperature data to obtain the CTE for specimen tested.

Coefficient of moisture expansion (CME) measurements were performed on the two neat resin systems, from dry to moisture saturation at 65°C. A constant relative humidity of 98 percent was maintained using distilled water in plexiglas moisture chambers. All CME tests were conducted using the automated moisture expansion test facility which is shown in Figure 5. CME measurements are accomplished by using two identical specimens for each test. Both specimens are cut to 70 mm (2.75 in.) by 70 mm (2.75 in.) square and then surface ground to a thickness of 0.9 mm (0.035 in.). This large square specimen of very small thickness is used to allow the assumption of one-dimensional diffusion during the moisture absorption process (i.e., edge effects are

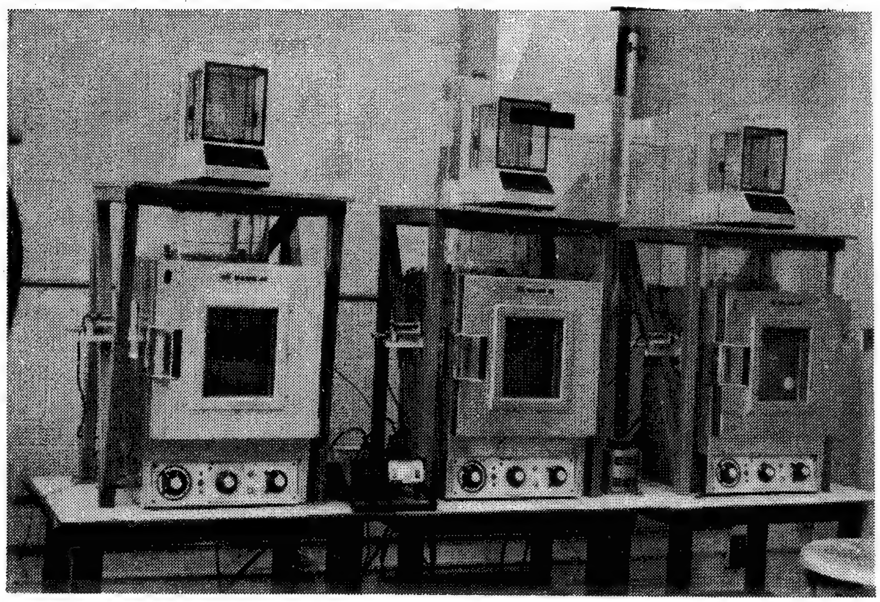

Figure 5. Moisture Expansion Coefficient Chambers with Electronic Balances on Top and LVDT's Mounted on the Side.

negligible). One specimen is hung from an electronic balance, which measures the weight gain due to moisture uptake as a function of time. A second identical specimen is placed in a quartz-tube dilatometer and an LVDT measures the in-plane linear expansion of this specimen simultaneously in the same moisture chamber. Using these two parameters, the strain with respect to moisture absorption is calculated and then curve-fit using a linear regression routine. The strain versus moisture curves are typically linear, resulting in a constant value of CME.

3.4 Composite Specimen Fabrication

The four carbon fiber-reinforced composites tested during this program were cut from plates supplied by NASA-Langley. A water-cooled abrasive saw was used to cut the panels into 0° tension, 90° tension, 0° Iosipescu shear, 90° coefficient of thermal expansion, and 90° coefficient of moisture expansion specimens. All specimens were stored in dessicators prior to testing. Table 10 shows the test matrix for the two environmental conditions used in the composites testing. Only dry conditions were used in this composites testing.

All static testing was performed using an Instron Model 1125 electromechanical testing machine. A BEMCO Model FTU 3.8 environmental chamber was used to maintain the desired elevated test temperatures. A Hewlett-Packard Model 21 MX-E mini-computer was used to record and reduce all data. A CDC Cyber 760 computer was used to generate all plots of material properties and groupings of stress-strain plots.

A standard straight-sided tabbed specimen as described in ASTM Standard D3039 [4] was used for all longitudinal tension testing. The specimens were 300 mm (9 in.) long by 12.7 mm (0.5 in.) wide by 1.0 mm (0.04 in.) thick. Each specimen had glass fabric/epoxy tabs 64 mm (2½ in. long) bonded on each end to ensure adequate gripping during testing. Instrumentation included two extensometers, one to measure axial strain and a second to measure transverse strain for each test. Complete stress-strain curves were generated. Poisson's ratio was calculated using the measured longitudinal and transverse strains. Figure 6 shows the typical extensometer arrangement used on the longitudinal tensile specimens.

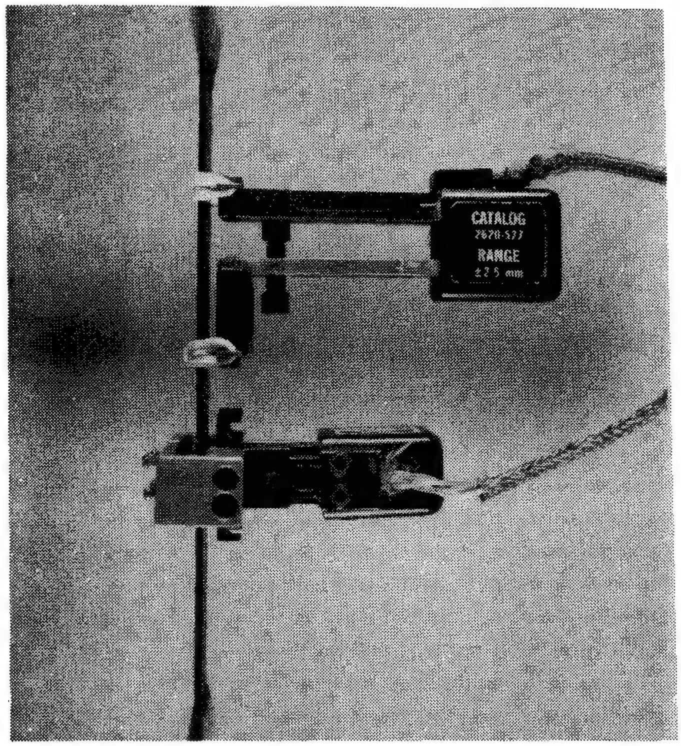

Figure 6. Typical Extensometer Arrangement used on the Unidirectional Composite Longitudinal Tension Test Specimens.

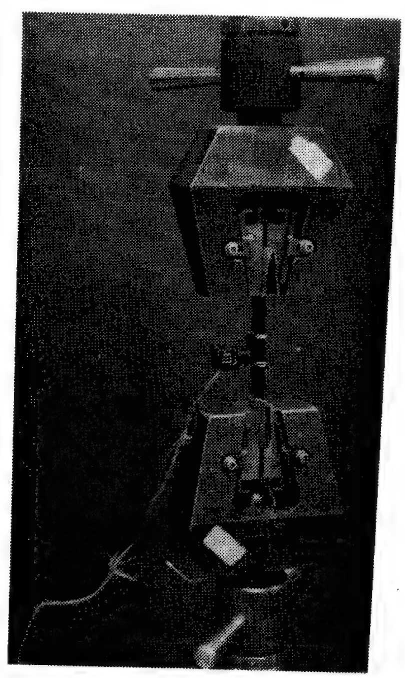

Figure 7. Composite Transverse Tension Test Configuration.

Standard straight-sided untabbed specimens as described in ASTM Standard D3039 [4] were used for all transverse tension testing. Specimens were 152 mm (6.0 in.) long by 25 mm (1.0 in.) wide by 2.0 mm (0.08 in.) thick. Pieces of emery cloth were placed between the specimen and grips in the grip areas to prevent specimen damage and to preclude premature failures in the grips. One extensometer was mounted on each specimen to record the complete stress-strain response to failure. Figure 7 shows a typical transverse tension test configuration, including wedge grips and extensometer.

The Iosipescu shear test method as described in Reference [8,9,10] was used for all in-plane shear testing. Specimens were 76 mm (3.0 in.) long by 19 mm (0.75 in.) wide by 2 mm (0.08 in.) thick. Figure 8 shows a typical specimen mounted in the Iosipescu shear test fixture. A 90° notch was ground in each edge of the specimen and then a two-element strain gage rosette was bonded in the gage section to measure shear strain.

Transverse coefficient of thermal expansion (CTE) test specimens were 127 mm (5.0 in.) long by 9.5 mm (0.375 in.) wide by 2.0 mm (0.08 in.) thick. Testing was performed using a microprocessor controlled quartz-tube dilatometer and an LVDT. The apparatus is shown in Figure 4. Axial thermal expansion tests were not performed because of the very low values of CTE expected, these being below the reasonable sensitivity of the dilatometer apparatus. Two thermal excursions between -40°C and 121°C were performed on three test specimens for each material. Data were acquired on the heat-up portion of each cycle only. A linear regression curve-fit was performed on the length versus temperature data points to obtain a CTE value for each specimen.

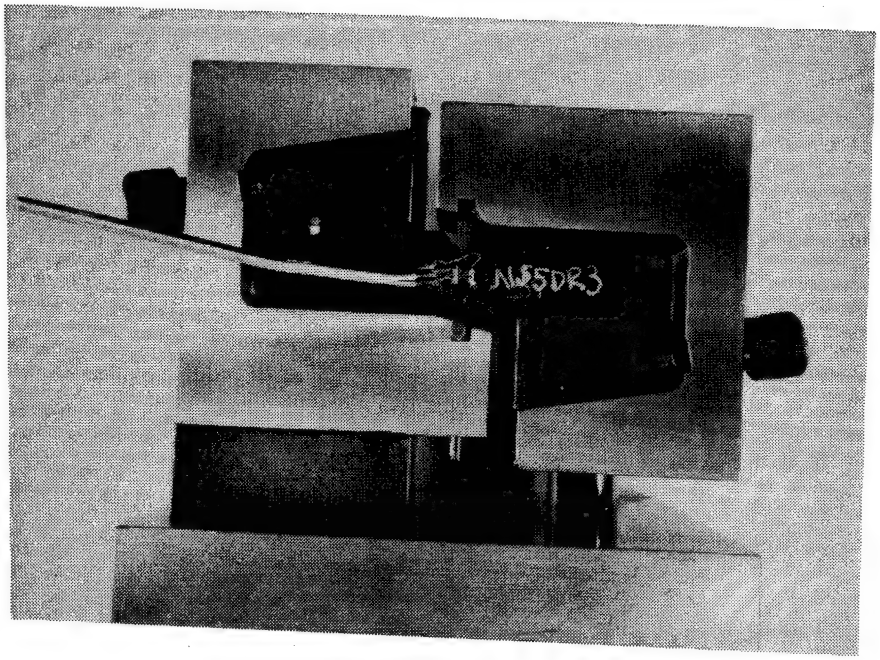

Figure 8. Iosipescu Shear Specimen Mounted in the Test Fixture

Transverse coefficient of moisture expansion specimens were 70 mm (2.75 in.) square by 0.9 mm (0.035 in.) thick. Only transverse CME tests were performed on the composites because of the limited sensitivity of the quartz tube dilatometer, as previously discussed. All CME tests were performed at 98 percent relative humidity and 65°C from dry to saturation. The procedure is described in Section 3.3 of this report.

SECTION 4

NEAT RESIN RESULTS

4.1 Neat Resin Tension Test Results

Engineering constants measured included Young's modulus, E, ultimate stress, σ_u, ultimate strain, ϵ_u, and Poisson's ratio, ν. Complete stress-strain curves to failure were recorded. Individual test results and stress-strain curves are included in Appendices A and B, respectively. Summary tables were presented in Section 1.

Average tensile strengths are shown in Figure 9 for the two neat resins, at three test temperatures for the CYCOM 1806 epoxy and four test temperatures for the ERX-4901B(MPDA) epoxy. The CYCOM 1806 epoxy maintained reasonable strength with increasing temperature while dry but degraded significantly when moisture-saturated. The ERX-4901B(MPDA) strengths were essentially nil at all moisture-saturated conditions. No tensile properties were measured for the ERX-4901B (MPDA) at 121°C, wet due to its significant softening at that condition. If the application for the ERX-4901B(MPDA) were in a controlled dry environment it would perform very well, however.

Dry tensile strengths for both resin systems were greater than 70 MPa (10 ksi) at room temperature. The average strength for the ERX-4901B(MPDA), at 97 MPa (14.1 ksi), was almost as high as the 109 MPa (15.8 ksi) ERX-4901A(MDA) strength measured in the previous year [2]. Tensile strengths decreased as test temperature increased, as expected.

Tensile moduli average values are shown in Figure 10. The CYCOM 1806 retained its stiffness well over the full range of test temperatures, although the average values were somewhat lower than those of

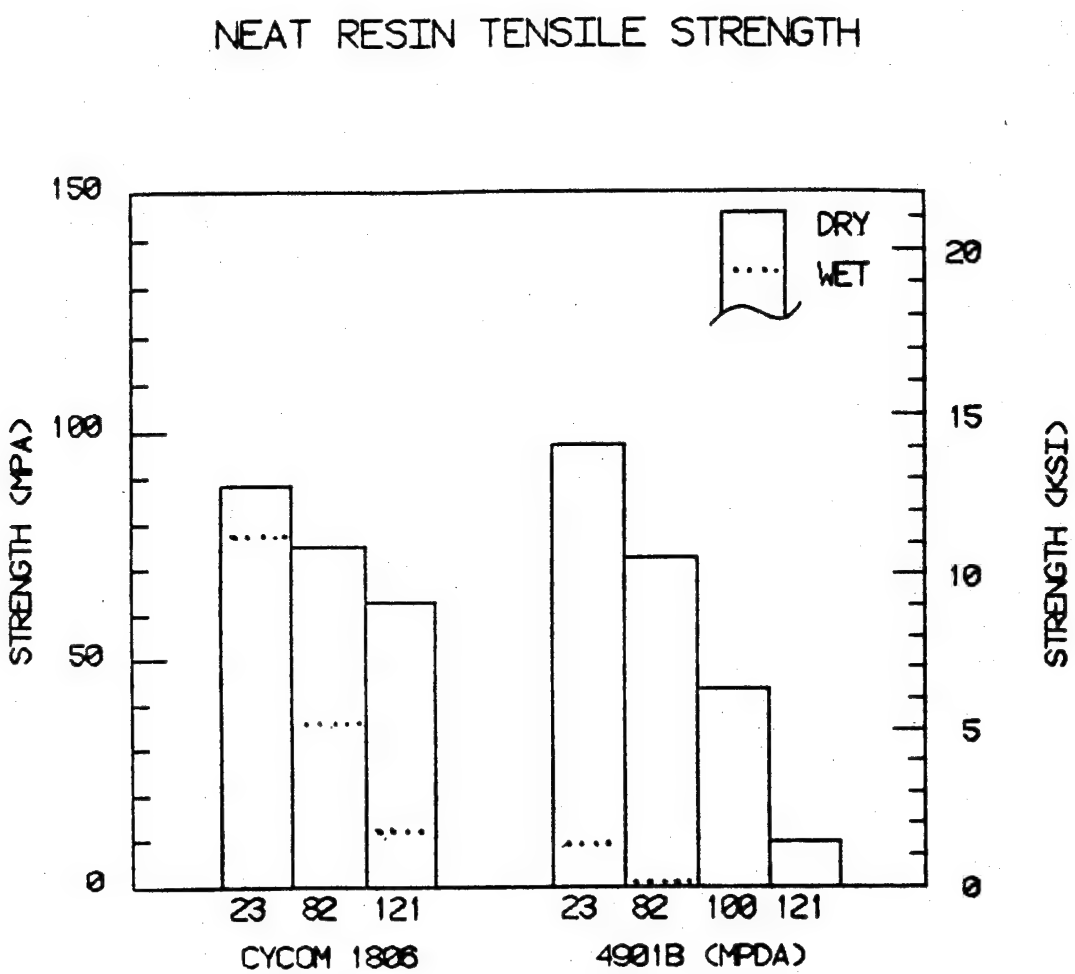

Figure 9. Neat Resin Tensile Strength as a Function of Temperature and Moisture.

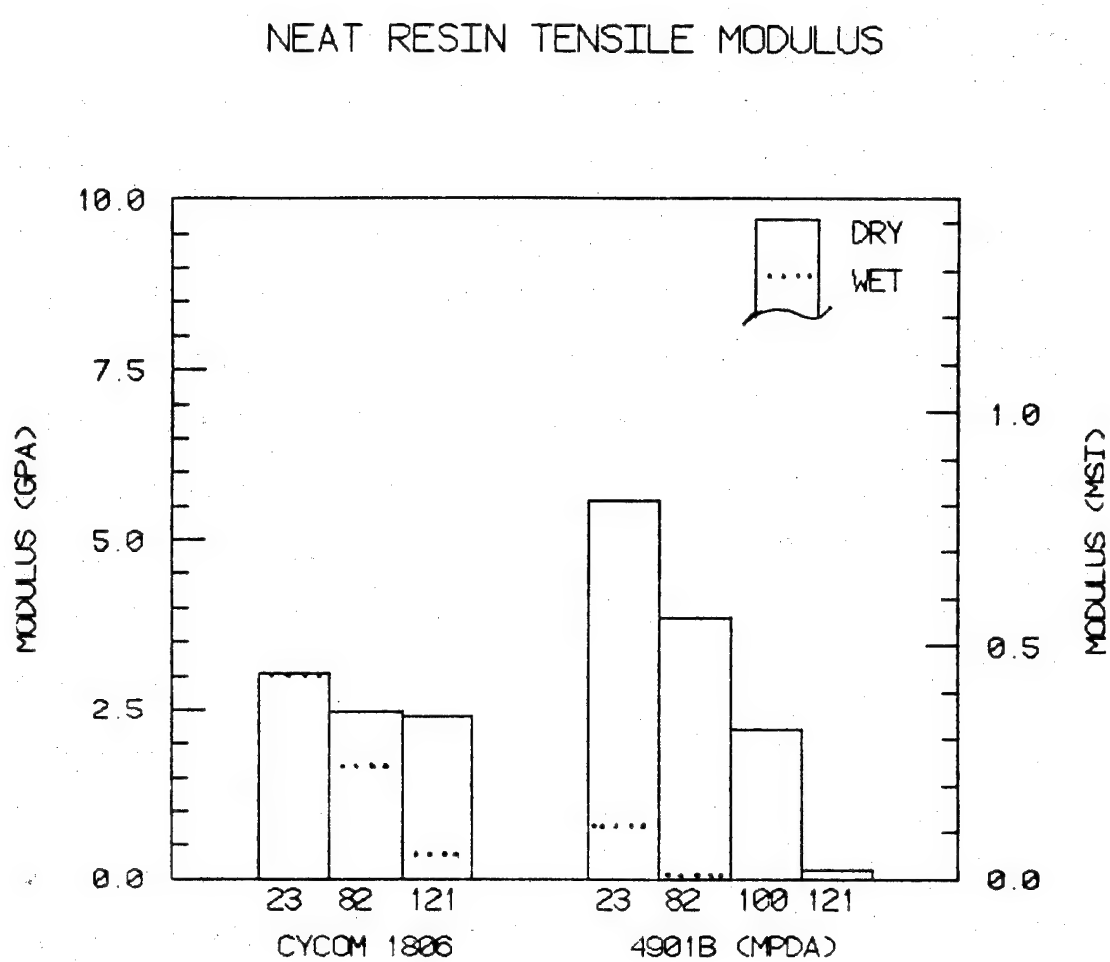

Figure 10. Neat Resin Tensile Modulus as a Function of Temperature and Moisture.

most resins previously tested. The ERX-4901B(MPDA), at 5.6 GPa (0.81 Msi), recorded the highest stiffness value of all neat resins tested. This was even slightly higher than that of the ERX-4901A(MDA) tested in the previous year. Unfortunately, the ERX-4901B(MPDA) modulus values decreased rapidly above 100°C, and were quite low at all test temperatures when the material was moisture-saturated.

All tensile test specimens failed straight across the gage section, similar to those in the previous report [2]. Figure 11 shows a typical CYCOM 1806 tensile specimen failure. Figure 12 shows two ERX-4901B (MPDA) specimens, one untested and one tested at the 121°C, dry condition. No fracture occurred, but some necking of the specimen was observed. This behavior was also seen in the ERX-4901A(MDA) epoxy tested in the prior study [2]. Failure was defined as the point where load dropped at the end of the test after necking had occurred.

Ultimate tensile strain average values are shown in Figure 13. CYCOM 1806 strains increased slightly with test temperature when in a dry condition. After moisture saturation the CYCOM 1806 strains tripled over the dry values above room temperature with the room temperature, wet value being only slightly higher than the room temperature dry value. Ultimate tensile strains for the CYCOM 1806 were much higher than the baseline 3502 epoxy strains at all test conditions. The ERX-4901B ultimate tensile strains were typically lower than the CYCOM 1806 values but were slightly higher than the baseline 3502 epoxy values at most test conditions.

4.2 Neat Resin Shear Test Results

Shear properties measured included shear modulus, G, shear strength, τ_u, and ultimate shear strain, γ_u. Complete shear stress-

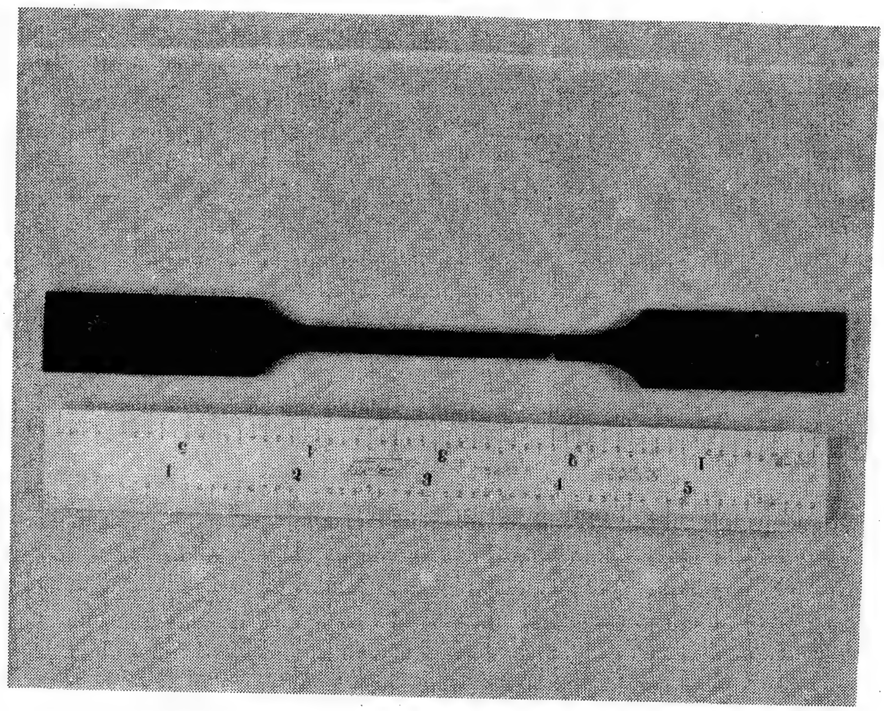

Figure 11. Typical Failed CYCOM 1806 Tension Specimen

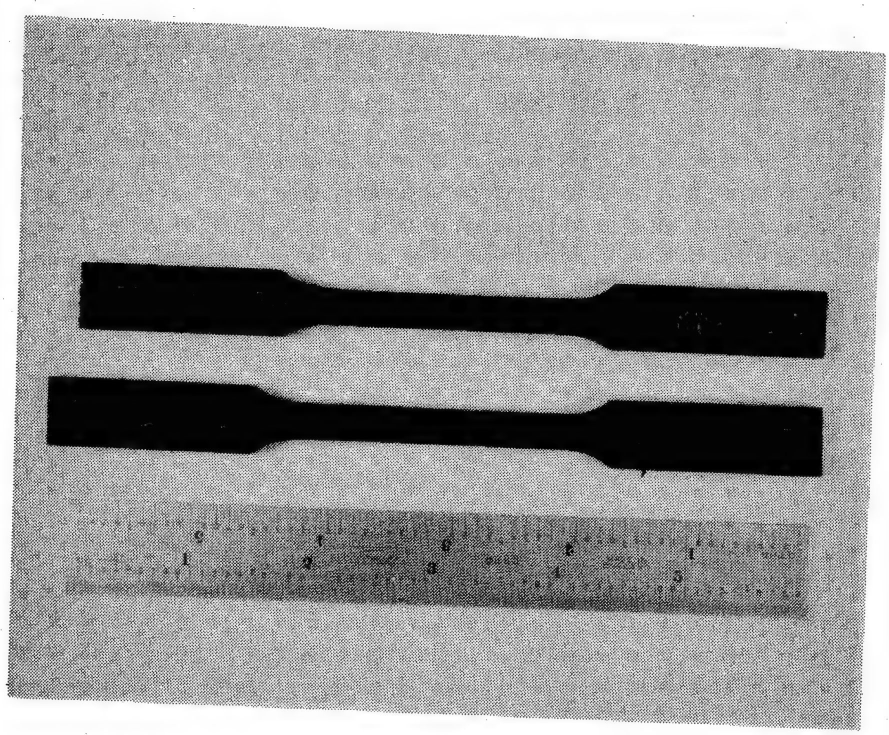

Figure 12. Typical Failed ERS-4901 (MPDA) Tension Specimen Tested at the 120°C, dry condition (bottom) and an untested specimen (top).

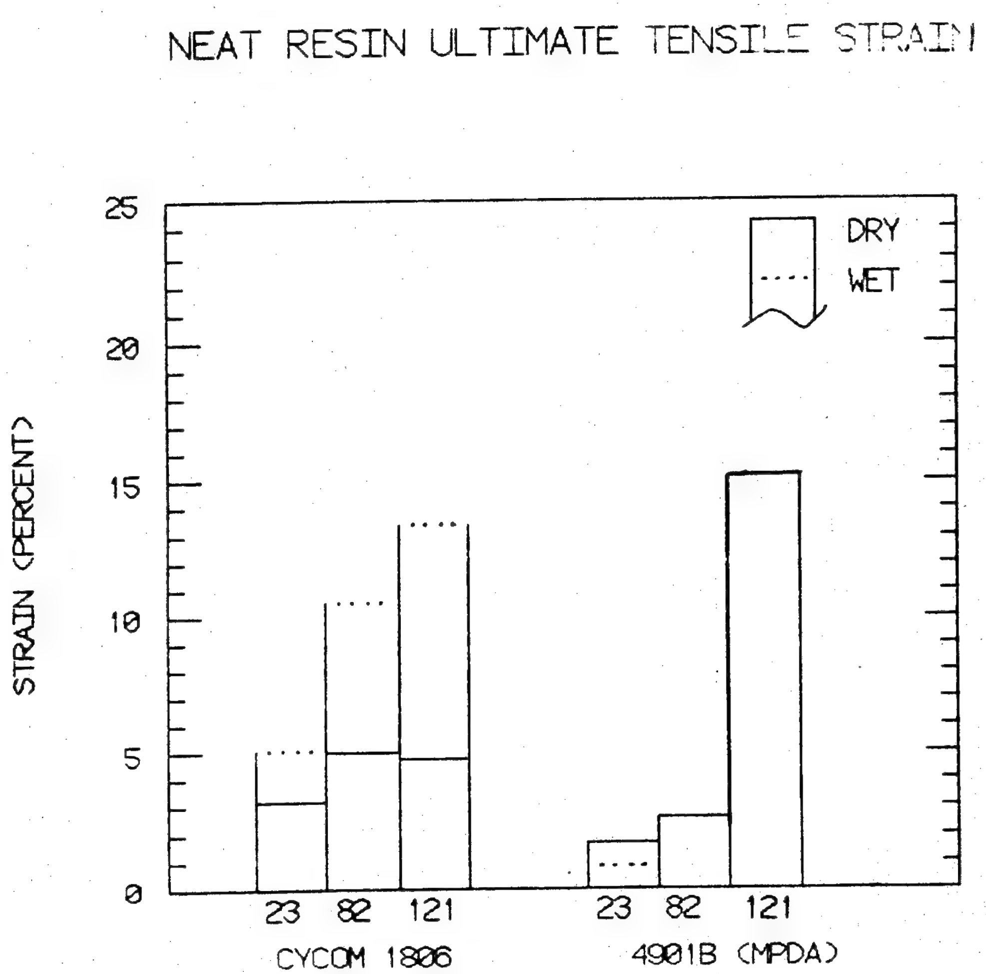

Figure 13. Neat Resin Ultimate Tensile Strain as a Function of Temperature and Moisture.

shear strain curves to failure were recorded. Individual test results and shear stress-shear strain curves are included in Appendices A and B, respectively. Summary tables were included in Section 1.

Figure 14 presents the average shear strengths for the CYCOM 1806 and ERX-4901B(MPDA) epoxies tested. The ERX-4901B(MPDA) recorded the highest shear strength of all the neat resins tested to date, exceeding even the ERX-4901A(MDA) value obtained in the prior program [2]. The 127 MPa (18.4 ksi) is extremely high for neat resins and, taken with it's high tensile strength and stiffnesses, make the ERX-4901B(MPDA) epoxy a unique material system for reinforced composites. Unfortunately, it's material properties fall quickly at elevated temperatures, and even more rapidly after being exposed to moisture. The CYCOM 1806 epoxy performed quite well in shear, exhibiting degradation similar to other resin systems studied. The CYCOM 1806 retained its shear strength after moisture saturation as well as any previous resin system studied.

Shear modulus average values are plotted in Figure 15. The CYCOM 1806 epoxy shear stiffness values were only slightly lower than those of previous resins tested, and it retained its shear stiffness well at all six environmental conditions. The ERX-4901B(MPDA) exhibited the highest room temperature, dry shear stiffness of any resin tested to date. Only a slight reduction was seen at the intermediate temperature, dry condition, but at other conditions it again showed a dramatic drop in shear modulus values, as expected. No shear properties were measured for the ERX-4901B(MPDA) epoxy at the 121°C, wet condition due to its significant softening at this condition.

Ultimate shear strain average values are shown in Figure 16. CYCOM 1806 shear strains were quite high being from 14-20 percent at the six

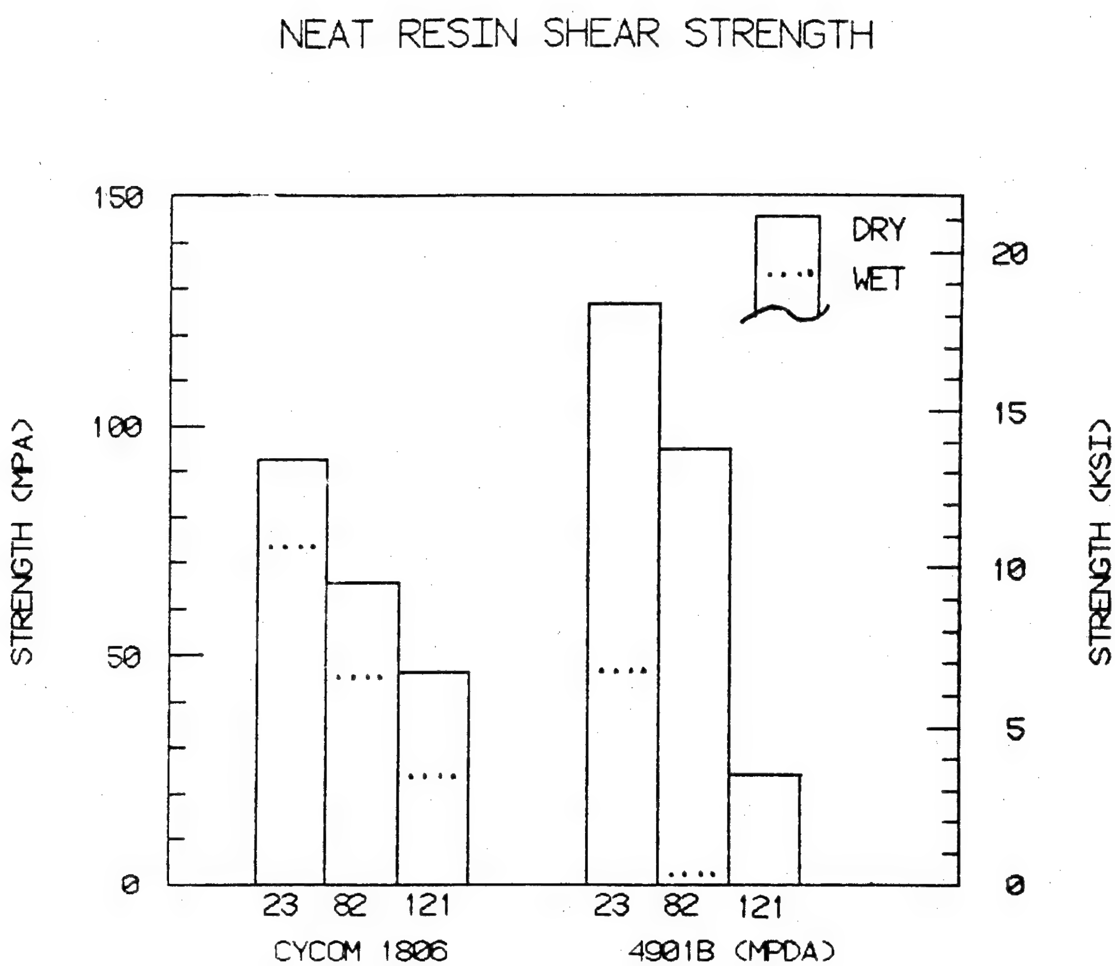

Figure: Neat Resin Shear Strength as a Function of Temperature and Moisture.

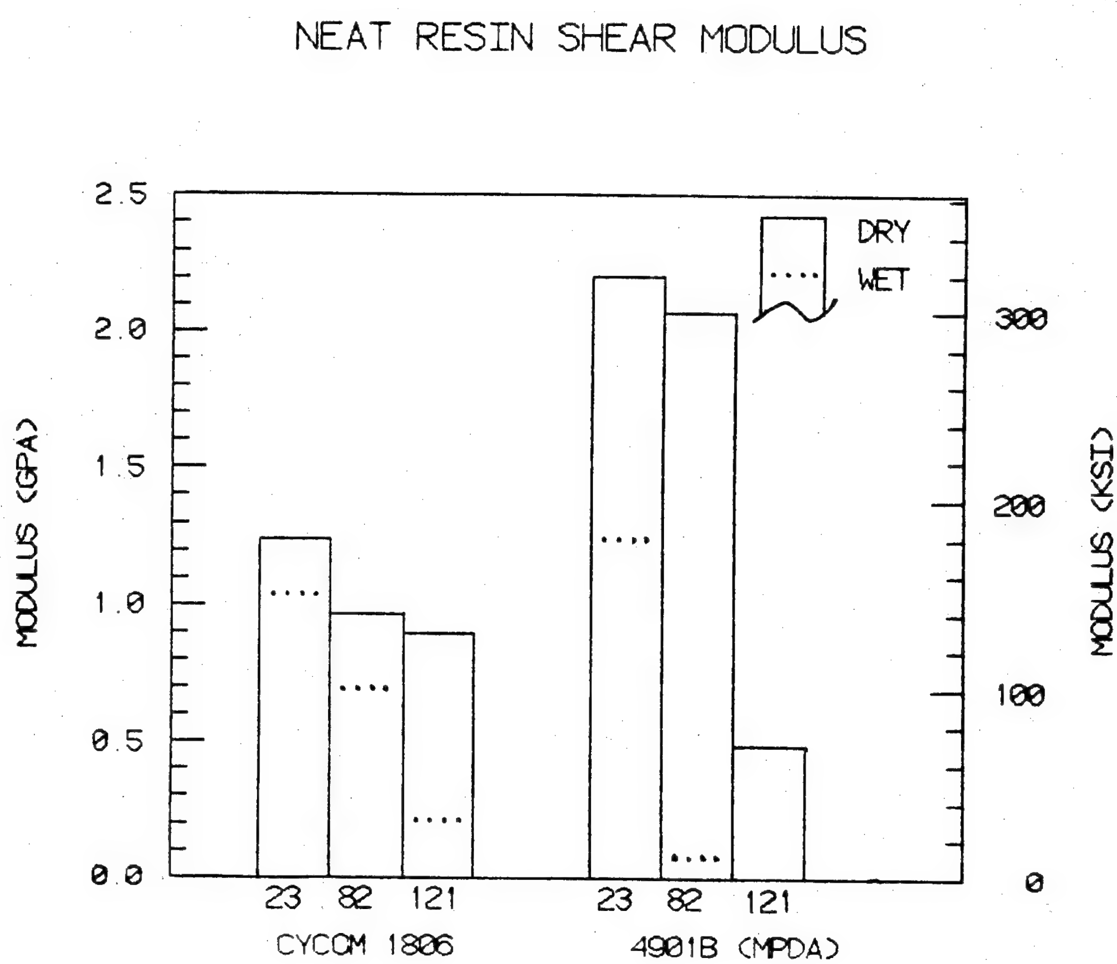

Figure 15. Neat Resin Shear Modulus as a Function of Temperature and Moisture.

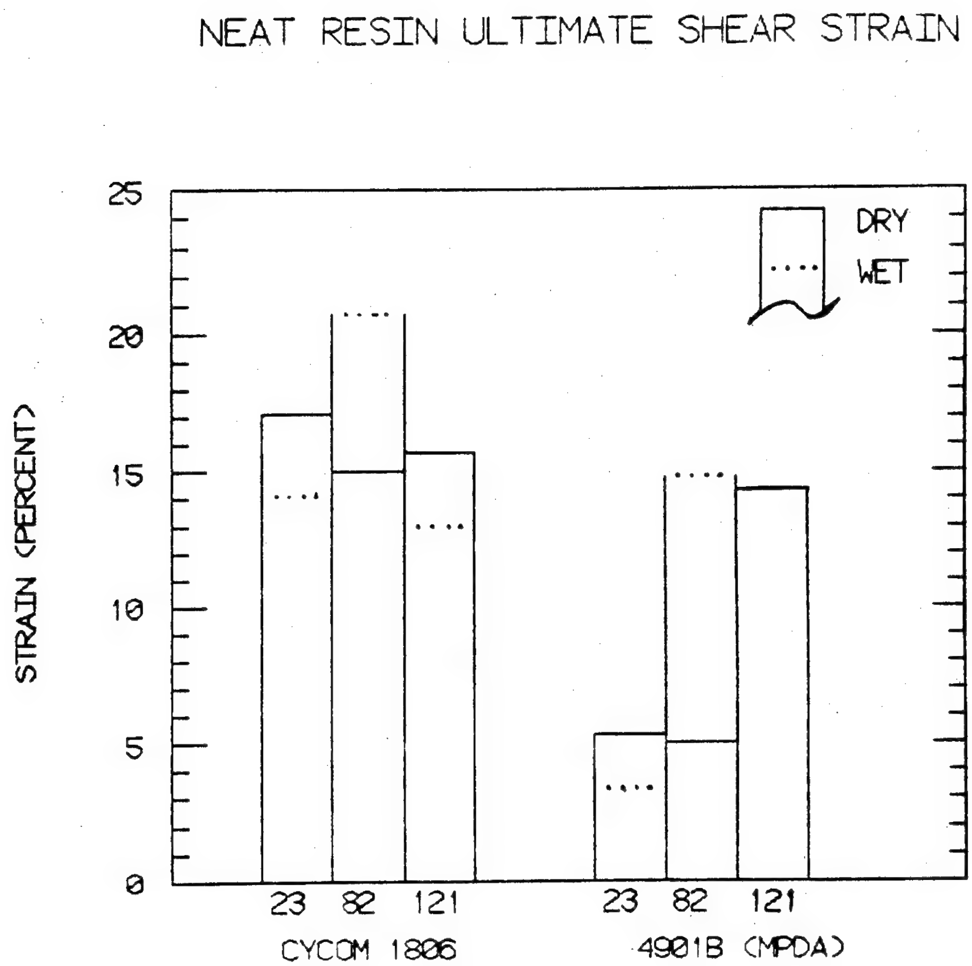

Figure 16. Neat Resin Ultimate Shear Strain as a Function of Temperature and Moisture.

test conditions. These values were 4 to 5 times the 3502 epoxy baseline shear strains recorded. The ERX-4901B epoxy shear strain was similar to the 3502 shear strain at the room temperature, dry condition, but increased three-fold at elevated test temperatures and after being moisture saturated.

Figure 17 shows a typical failed CYCOM 1806 dogbone-shaped torsion specimen. It will be noted that the angle of fracture is on a 45 degree plane, implying the specimen failed on the tensile stress plane during the torsional shear test. Figure 18 shows a typical failed ERX-4901B (MPDA) torsional shear specimen. Its failure is similar to that of the CYCOM 1806 at low test temperatures. The ERX-4901B(MPDA) epoxy softened considerably at elevated temperatures, and after being exposed to moisture, resulting in the typical twisting failure seen in Figure 19. Fracture was initiated only after a large rotation of the cylindrical specimen, as seen in Figure 19.

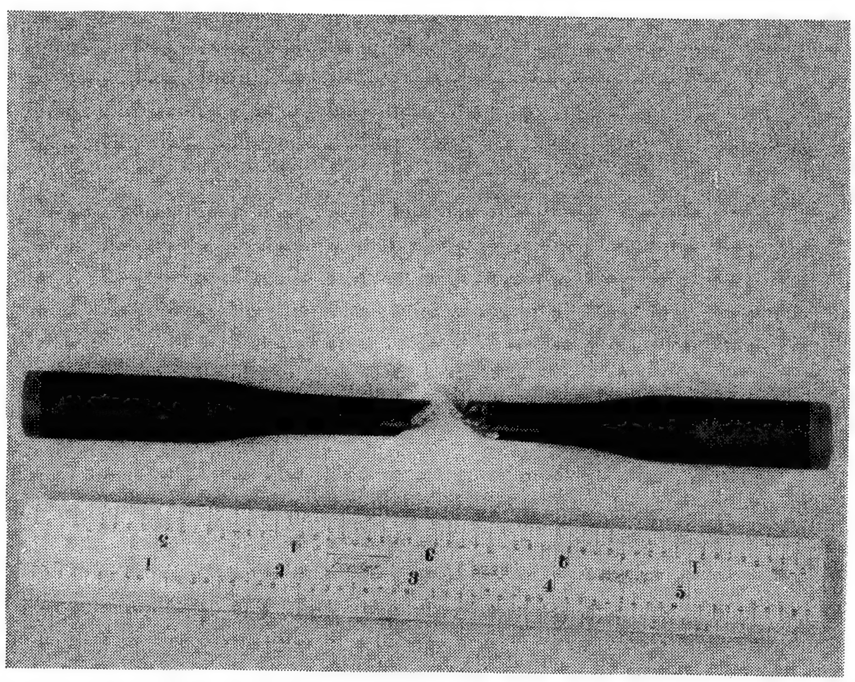

Figure 17. Typical Failed CYCOM 1806 Dogbone-Shaped Torsion Specimem at Room Temperature, dry condition.

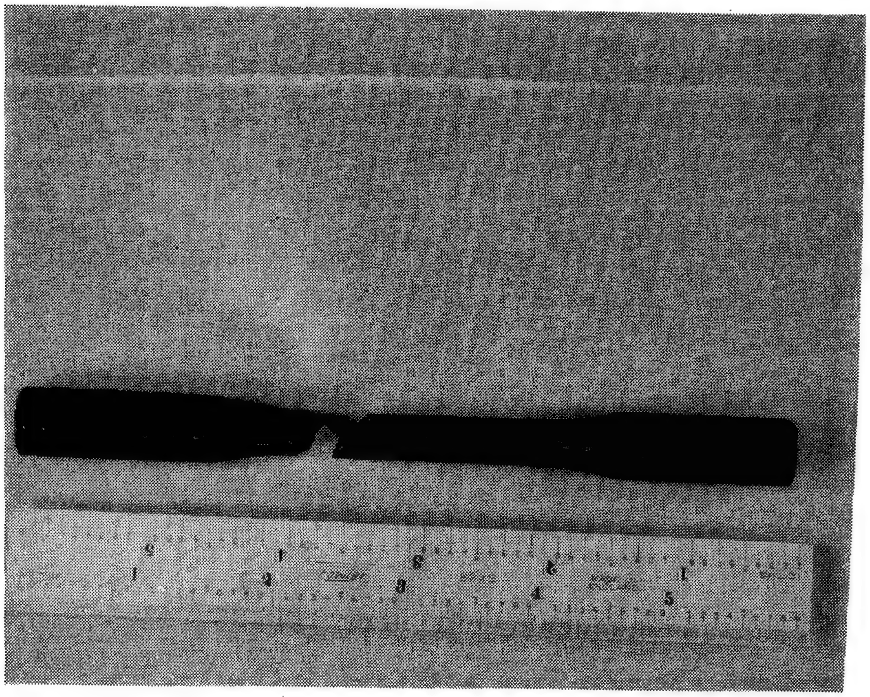

Figure 18. Typical Failed ERX-4901B (MPDA) Dogbone-Shaped Torsion Specimen at Room Temperature, Dry Condition.

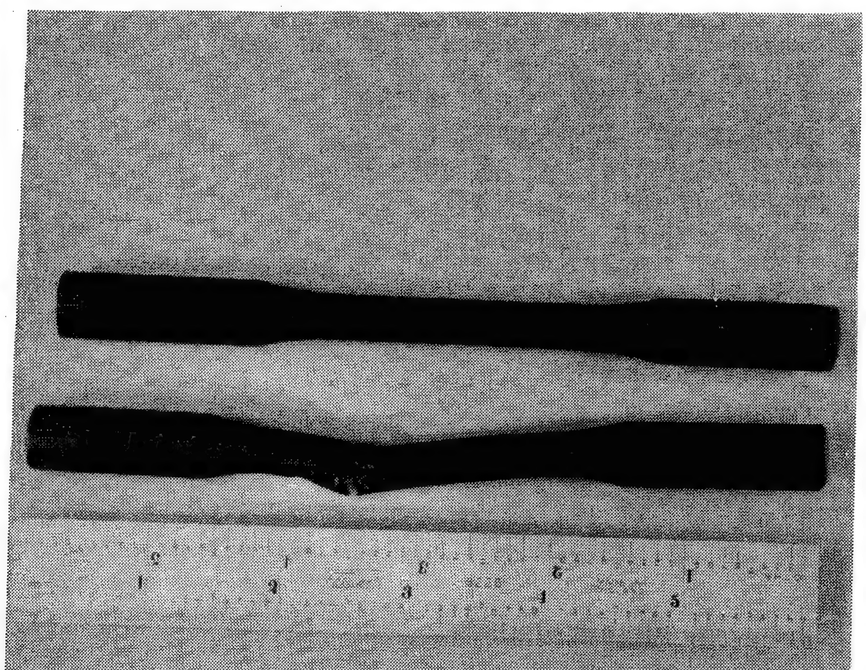

Figure 19. Typical Failed ERX-4901B (MPDA) Dogbone-shaped Torsion Specimen Tested at 82°C, Moisture-Saturated Condition, with Untested Specimen Shown for Comparison.

4.3 Neat Resin Fracture Toughness Test Results

Mode I strain energy release rate values were measured for the CYCOM 1806 epoxy and the ERX-4901B(MPDA) epoxy at six and four environmental conditions, respectively. The ERX-4901B(MPDA) epoxy became too soft to measure any properties at the highest test temperature. Average G_{IC} values for the CYCOM 1806 and ERX-4901B(MPDA) are plotted in Figure 20. Both resins are equal in toughness to the resins tested in the prior program [2]. The CYCOM 1806 epoxy did show a large increase in G_{IC} at the 82°C dry test condition, and at the 23°C, moisture-saturated condition. The ERX-4901B(MPDA) epoxy apparently weakened too quickly to record any increase in G_{IC} at any test condition different from 23°C, dry condition.

Average strain energy release rate values for the two neat resins are given in Table 7. Individual G_{IC} values are given in Appendix A.

4.4 Neat Resin Coefficient of Thermal Expansion Results

Table 11 lists the average CTE results for the two neat resins. The CYCOM 1806 exhibited linear expansion behavior, yielding a constant value of CTE over the test temperature range, in both the dry and the moisture-saturated condition. The ERX-4901B(MPDA) exhibited nonlinear expansion behavior over the test temperature range. Table 11 includes the calculated CTE values at three temperatures for the ERX-4901B(MPDA) epoxy, as well as the equations used for the calculations. Using these equations, the CTE at any temperature of interest can be calculated.

Both resin systems showed an increase in CTE after being moisture-saturated, as observed in all previous resin testing also [1,2]. Individual curves and data are included in Appendix B of this report.

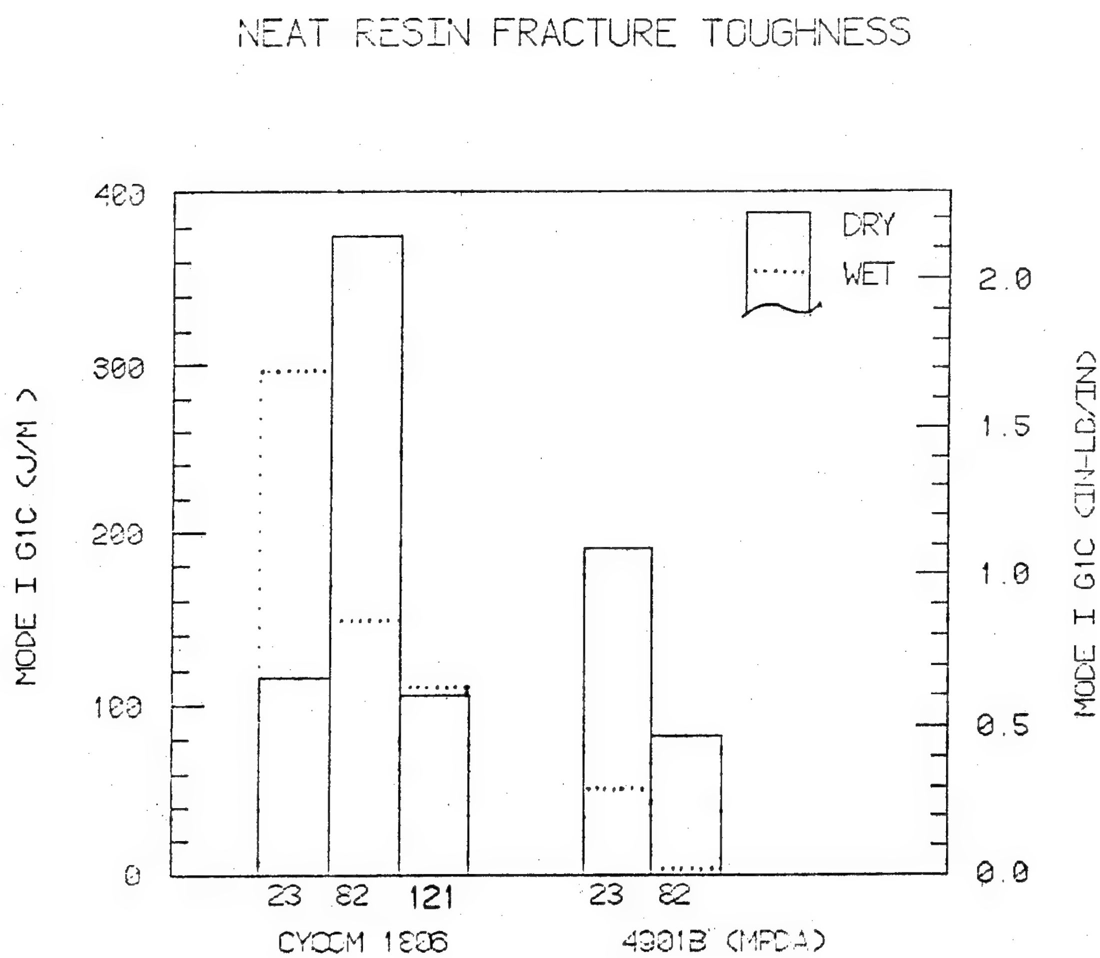

Figure 20. Neat Resin Fracture Toughness as a Function of Temperature and Moisture.

Table 11

Average Coefficients of Thermal Expansion For the Two Neat Resin Systems Tested

Resin System	Coefficient of Thermal Expansion CTE ($10^{-6}/°C$) Dry			Moisture Saturated		
CYCOM 1806	58.2			63.2		
	-60°C	23°C	93°C*	-60°C	23°C	93°C#
ERX-4901B (MPDA)	22.6	61.6	94.4	13.5	90.5	155.4

1) $$\text{DRY CTE} = 5.078 \times 10^{-5} + 4.689 \times 10^{-7} \times T(°C)$$

2) $$\text{Moisture Saturated CTE} = 6.917 \times 10^{-5} + 9.276 \times 10^{-7} \times T(°C)$$

---

*CTE values calculated using Eq. (1).
#CTE values calculated using Eq. (2).

The CYCOM 1806 epoxy CTE values were slightly higher than the Hercules 3502 epoxy baseline resin in both the dry and wet conditions. The ERX-4901B(MPDA) exhibited highly nonlinear behavior compared to the linear behavior of the ERX-4901A(MDA) epoxy observed previously [2].

4.5 Neat Resin Coefficient of Moisture Expansion Results

Average coefficients of moisture expansion and moisture saturation weight gains are given in Table 12. The measured CME of the CYCOM 1806 was slightly lower than that of the 3502 baseline epoxy, and exhibited about 60 percent of the equilibrium moisture content of the 3502 epoxy. The ERX-4901B(MPDA) epoxy had a slightly lower CME than the ERX-4901A(MDA) version, and recorded the highest moisture saturation

Table 12

Average Coefficients of Moisture Expansion and Moisture Saturation Weight Gains For the Two Neat Resin Systems Tested

Resin System	Coefficient of Moisture Expansion, CME (10^{-3}/%M)	Moisture Saturation Weight Gain (%M)
CYCOM 1806	2.53	2.9
ERX-4901B(MPDA)	1.00	10.2

value of all ten neat resins tested to date. The ERX-4901B(MPDA) epoxy specimens also exhibited some surface blistering, which had not been observed for any other resin system studied to date.

4.6 Relations Between Elastic Constants

Lack of satisfaction of the isotropic relation

$$G = \frac{E}{2(1+\nu)}$$

was again observed for the two additional resin systems tested. This behavior had been observed in the two previous studies [1,2]. Table 13 lists the elastic constants measured and calculated for the two latest epoxy systems.

As can be seen in Table 13, the calculated shear modulus, G, is almost always lower than the measured shear modulus. The calculated G values are based on the Young's modulus, E, and Poisson's ratio, ν, measured in tensile tests on the epoxies. This behavior is identical to that observed in the previous eight neat resin systems [2]. The CYCOM 1806 epoxy did agree to a higher degree at all conditions compared to the 20 percent variance witnessed in the two previous studies.

The ERX-4901B(MPDA) agreed with the isotropic relation relatively well at 23°C, dry, but diverged rapidly and to as great a degree as the

Table 13

Measured Versus Calculated Shear Moduli
For Two Neat Resin Systems

Neat Resin System	Measured Young's Modulus (GPa)	Measured Poisson's Ratio	Measured Shear Modulus (GPa)	Calculated Shear Modulus (GPa)	$\frac{G_{meas}-G_{calc}}{G_{meas}}$ (percent)
<u>23°C, Dry</u>					
CYCOM 1806	3.03	0.39	1.24	1.09	12
ERX-4901B(MPDA)	5.58	0.33	2.21	2.10	5
<u>82°C, Dry</u>					
CYCOM 1806	2.48	0.46	0.97	0.85	12
ERX-4901B(MPDA)	3.86	0.41	2.07	1.37	34
<u>121°C, Dry</u>					
CYCOM 1806	2.14	0.44	0.90	0.84	7
ERX-4901B(MPDA)	0.14	0.45	0.48	0.05	90
<u>23°C, Moisture-Saturated</u>					
CYCOM 1806	3.03	0.46	1.03	1.04	-1
ERX-4901B(MPDA)	0.76	0.48	1.24	0.26	79
<u>82°C, Moisture-Saturated</u>					
CYCOM 1806	1.65	0.44	0.69	0.57	17
ERX-4901B(MPDA)	--	--	--	--	--
<u>121°C, Moisture-Saturated</u>					
CYCOM 1806	0.34	0.38	0.21	0.12	43
ERX-4901B(MPDA)	--	--	--	--	--

ERX-4901A(MDA) epoxy tested in the previous year [2] when compared at elevated temperatures and after moisture conditioning. The Young's modulus for ERX-4901B(MPDA) at 121°C, dry was extremely low and probably resulted in the high error calculated between G measured and G calculated at this test condition.

No explanation for these discrepancies can be offered at this time. It is an interesting phenomenon and warrants additional study. No additional bulk modulus measurements have been completed on any of the neat resins of interest to allow that additional independent check on the elastic constants.

4.7 Additional Neat Resin Test Results

Additional tension and shear testing was performed on one neat resin from last year's program, viz, CYCOM 907 (BP907). Testing at only the -80°C, dry condition was done to add to the data base for the CYCOM 907, which is a model laboratory system. Table 14 gives average property values from both years for the CYCOM 907 at the four test temperatures utilized. Only dry specimens were tested at the cold temperature. Individual test results are given in Appendix A. Tensile and shear stiffness and strength values for the CYCOM 907 increased slightly from the room temperature values when it was tested at the subambient temperatures, and strain values dropped slightly. Poisson's ratio for the CYCOM 907 was quite low at the -80°C, dry test condition. The small drop of Poisson's ratio for the CYCOM 907 at the 121°C, dry test condition can be attributed to possible experimental error. The CYCOM 907 epoxy has a relatively low use temperature of 82°C and is quite soft at the 121°C temperature [11]. Fracture toughness values at the -80°C, dry condition, listed in Table 7, show a dramatic drop in strain energy release rate compared to the room temperature value measured last year [2].

TABLE 14

AVERAGE MATERIAL PROPERTIES FOR CYCOM 907 NEAT RESIN AT THE DRY CONDITION

Test Temp. (°C)	Tensile Strength (MPa)	(ksi)	Tensile Modulus (GPa)	(Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio	Shear Strength (MPa)	(ksi)	Shear Modulus (GPa)	(Msi)	Ultimate Shear Strain (percent)
-80	101	14.7	4.1	0.59	2.8	0.15	55	8.0	1.8	0.26	3.3
23[2]	86	12.5	3.3	0.47	3.7	0.42	45	6.5	1.2	0.17	3.3
82[2]	67	9.7	2.8	0.40	5.4	0.42	46	6.6	1.0	0.15	>6.0
121[2]	14	2.0	0.8	0.12	>8.2	0.38	28	4.0	0.8	0.11	>6.0

SECTION 5

UNIDIRECTIONAL CARBON FIBER REINFORCED COMPOSITE RESULTS

5.1 Introduction

All testing during the first two years of this grant had been performed on only neat resin materials, the data generated being used in the micromechanics analysis computer program to predict performance for carbon fiber-reinforced composites. These predictions had not been verified by experimental testing until this, the third year of the grant. Composite panels were supplied by NASA-Langley to allow testing of composites incorporating these neat resin systems. Four carbon fiber-reinforced composite materials were supplied in sufficient quantities to perform longitudinal tension, transverse tension, in-plane shear, transverse coefficient of thermal expansion, and transverse coefficient of moisture expansion testing. Engineering constants measured included axial and transverse moduli, E_{11} and E_{22}, shear modulus, G_{12}, tensile strengths, σ_{11} and σ_{22}, shear strength, τ_{12}, Poisson's ratio, ν_{12}, and ultimate strains, ϵ_{11}, ϵ_{22} and γ_{12}. Also measured were transverse thermal and moisture expansion coefficients, α_{22} and β_{22}.

5.2 Composite Fiber Volume and Void Volume Measurement Results

Fiber volume and void volume determinations were performed on the four carbon fiber-reinforced composites received from NASA-Langley.

Nitric acid was used to dissolve the matrix resin in the four composites. Three samples were digested for each composite, with the average values being given in Table 15. Individual fiber volume and void volume results are given in Appendix A.

All four materials exhibited similar fiber volumes and therefore any variances in material properties cannot be attributed to fiber volume variances.

Table 15

Average Fiber Volume and Void Volume Determinations for the Four Carbon Fiber-Reinforced Composites

Material System	Fiber Volume (percent)	Void Volume (percent)
AS4/3502	64.5	1.1
AS6/5245-C	63.1	1.1
T300/BP907	58.2	1.6
C6000/1806	63.4	1.8

Void volumes were also measured for the four composite material systems. As Table 15 indicates, void volumes were between 1 and 2 percent. Void volumes in similar aerospace materials are typically less than 1 percent. Measured void volumes here are only slightly greater than the 1 percent which probably had little effect on the results for this program.

5.3 Composite Longitudinal Tension Test Results

Complete stress-strain curves to failure were recorded for all tension tests. Individual stress-strain curves and test results are included in Appendices A and B.

Figure 21 is a plot of the axial tensile strengths for the four composite systems. The solid lines represent the room temperature, dry results while the dotted lines represent the results at 100°C, dry. It is difficult to compare the axial tension results between the materials due to the different types of carbon fibers incorporated in the four material systems. The AS4, C6000, and T300 high strength carbon fibers have similar stiffnesses and strengths [5,6,7], while the AS6 fiber stiffness is similar to those of the other three fibers, but it has a slightly higher strength [5]. This fact could explain the slightly higher tensile strength of the AS6/5245-C composite compared to the other three materials. Axial tension failures were quite typical of those commonly observed for unidirectional carbon-reinforced fiber epoxy composites in general, a typical failure being shown in Figure 22. Little change in tensile strength was seen at the elevated temperature test condition, which was as expected. The fiber dominates behavior in the axial direction and is relatively unaffected by the 100°C test temperature.

Axial tensile moduli values are shown in Figure 23. Little difference was found between the four composites, as expected because of the similar stiffness properties for the four fiber types. Small differences were seen in axial stiffness at the elevated temperature test condition. The 100°C test temperature was not high enough to produce a drop in axial stiffness since the carbon fiber completely dominates behavior in that test direction.

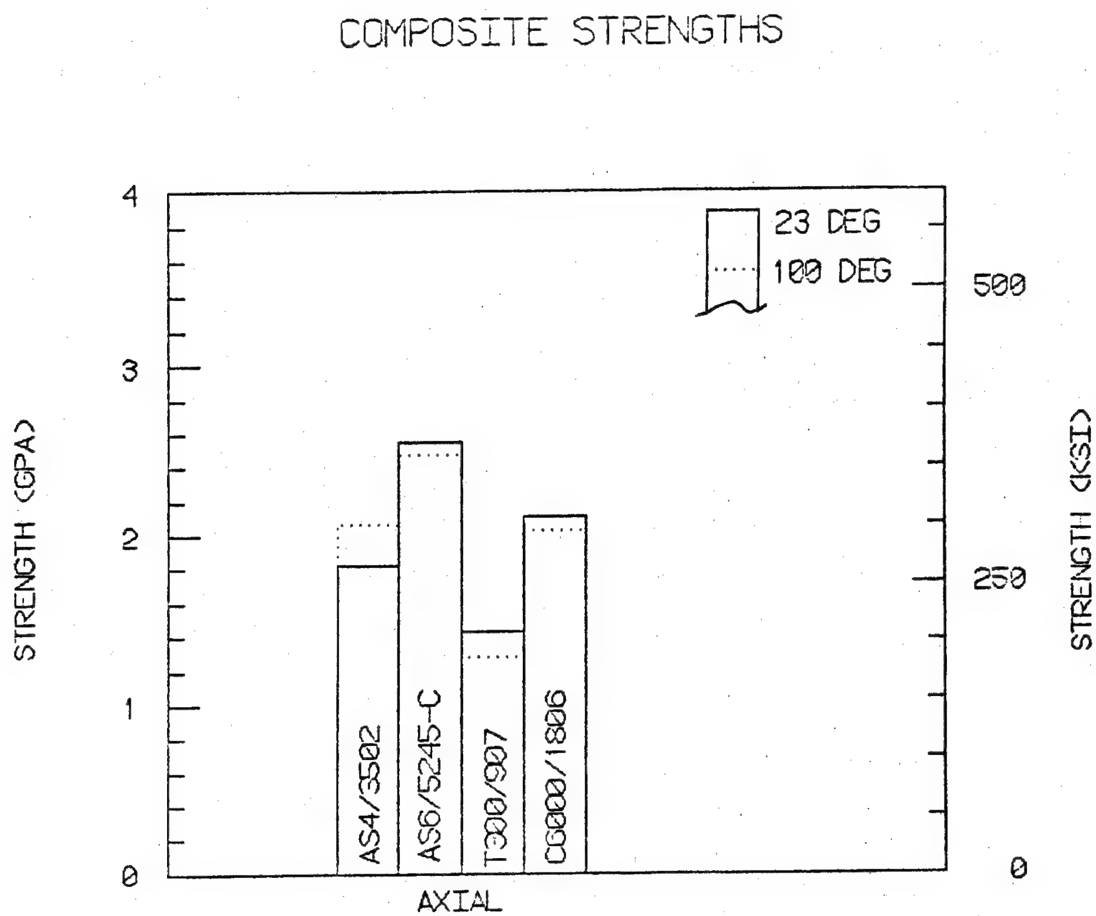

Figure 21. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Strengths.

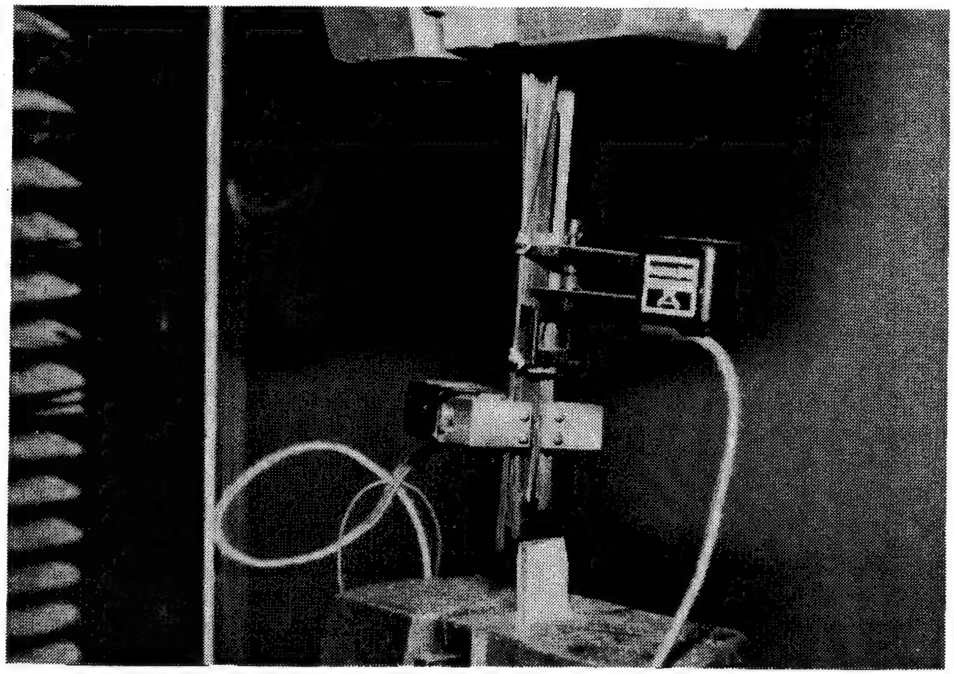

Figure 22. Typical Failed Unidirectional Composite Axial Tension Specimen.

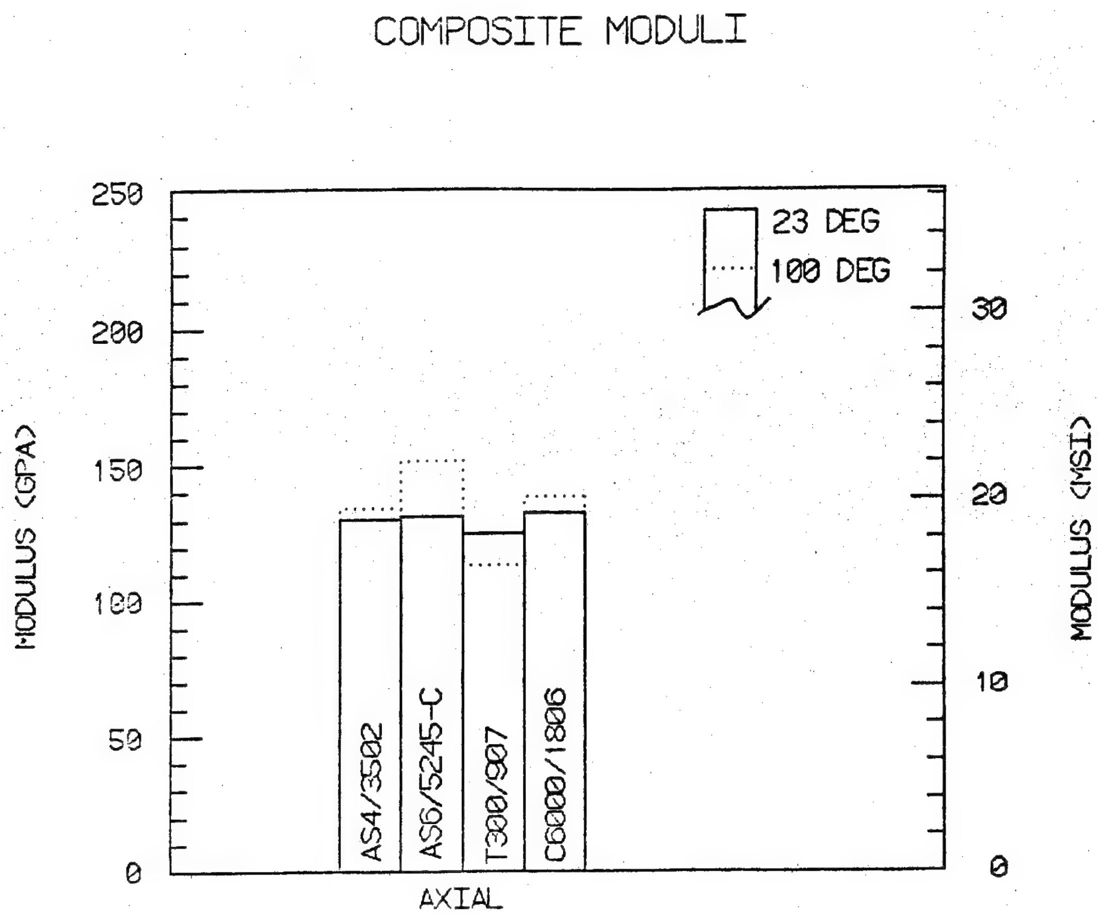

Figure 23. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Moduli.

Axial tensile strains are shown in Figure 24. This property is inherently dominated by the fiber used in the test. The AS6 and C6000 fibers have slightly higher ultimate strains, which are translated into the composite behavior.

Axial tension average test results are given in Table 8. Individual test results are included in Appendix A.

5.4 Composite Transverse Tension Test Results

Complete stress-strain curves to failure were also recorded for the transverse tension tests. Individual stress-strain curves and test results are given in Appendices A and B.

Figure 25 is a bar chart of transverse tensile strengths for the four composite systems. This property is highly dominated by matrix performance and also by the interaction between fiber and matrix. Room temperature transverse tensile strengths were similar for the four composites, but the T300/CYCOM 907 strength dropped dramatically at the 100°C test condition. Transverse tensile failure is characterized by a straight line fracture across the axis of the specimen, as seen in Figure 26.

Transverse tensile moduli are shown in bar chart form in Figure 27. Moduli values followed the neat resin trend values in most cases. At the 100°C test condition, the T300/CYCOM 907 composite modulus fell to one-half of its room temperature value, as expected, while the other composites retained their stiffnesses quite well. Transverse tensile ultimate strains are shown in Figure 28.

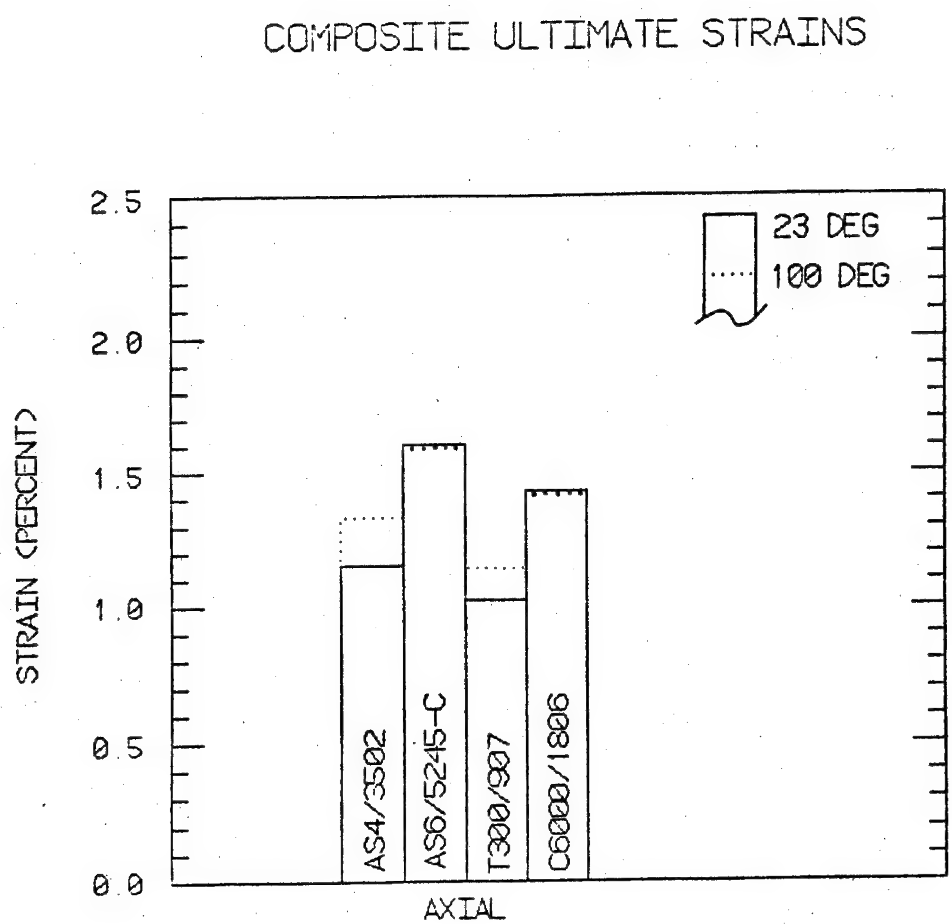

Figure 24. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Ultimate Strains.

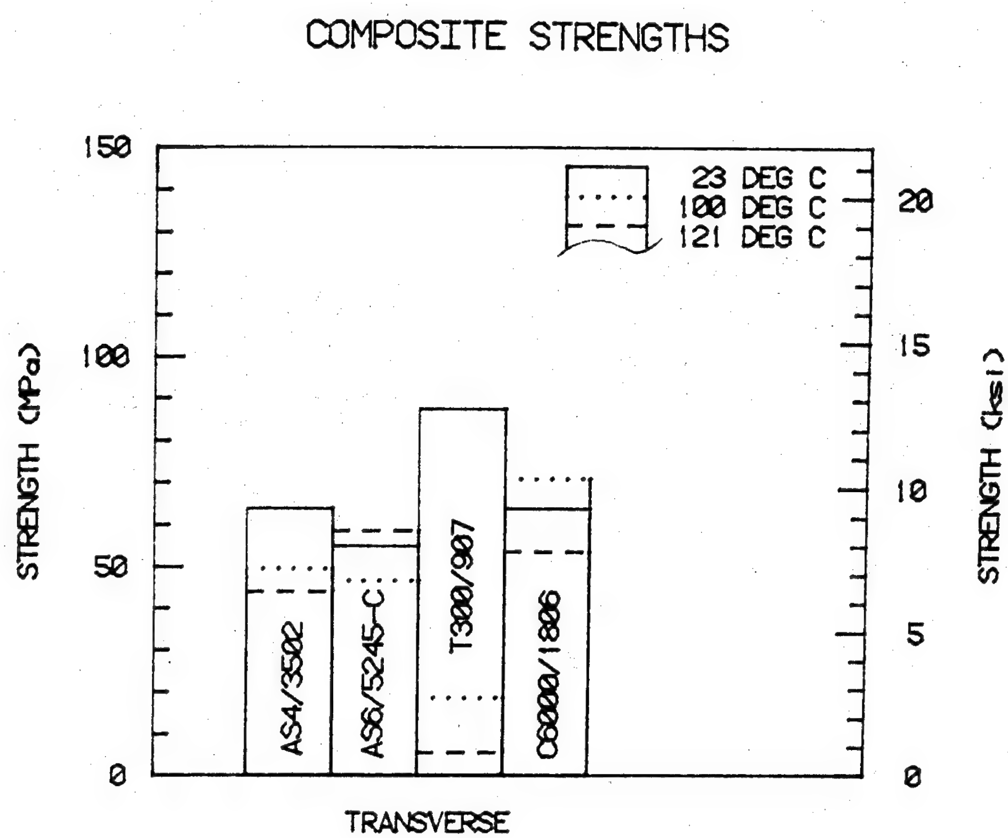

Figure 25. Unidurectional Carbon Fiber-Reinforced Composite Transverse Tensile Strengths.

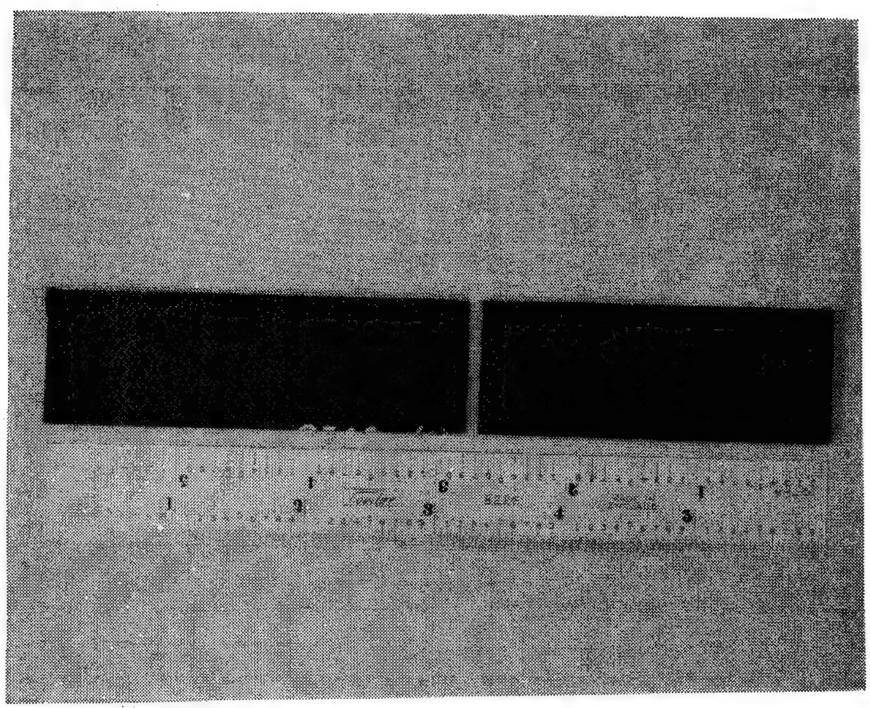

Figure 26. Typical Unidirectional Composite Transverse Tensile Failure.

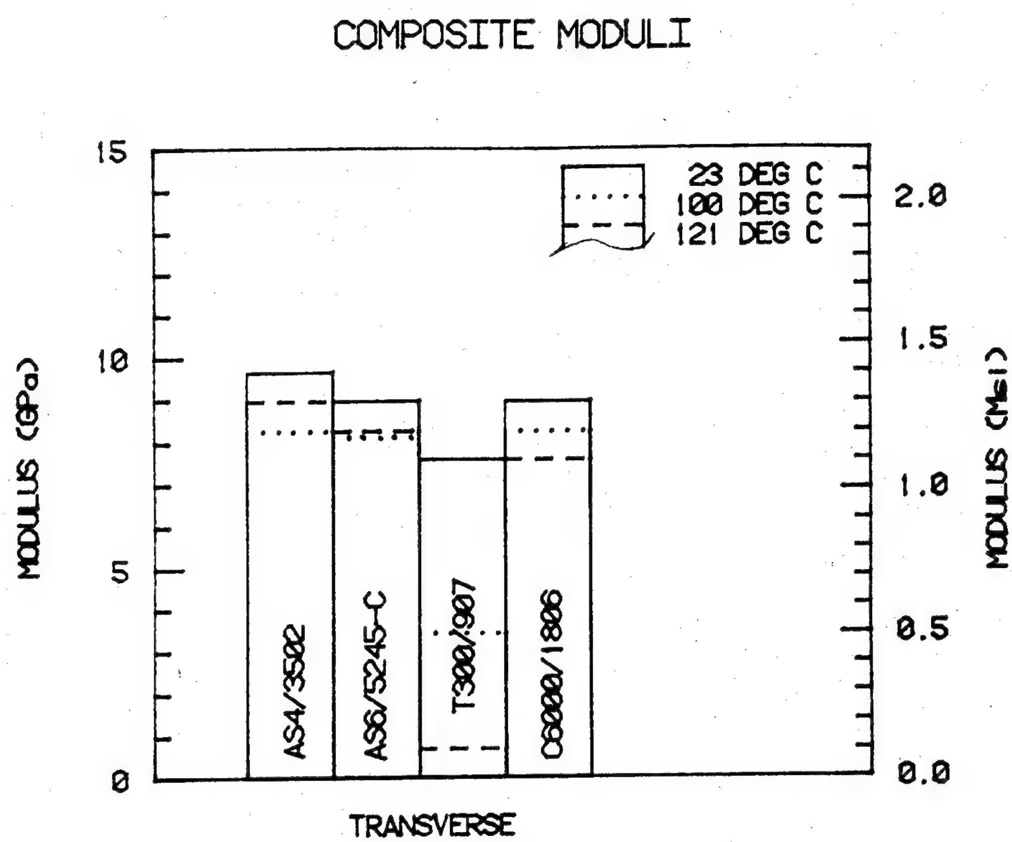

Figure 27. Unidirectional Carbon Fiber-Reinforced Composite Transverse Tensile Moduli.

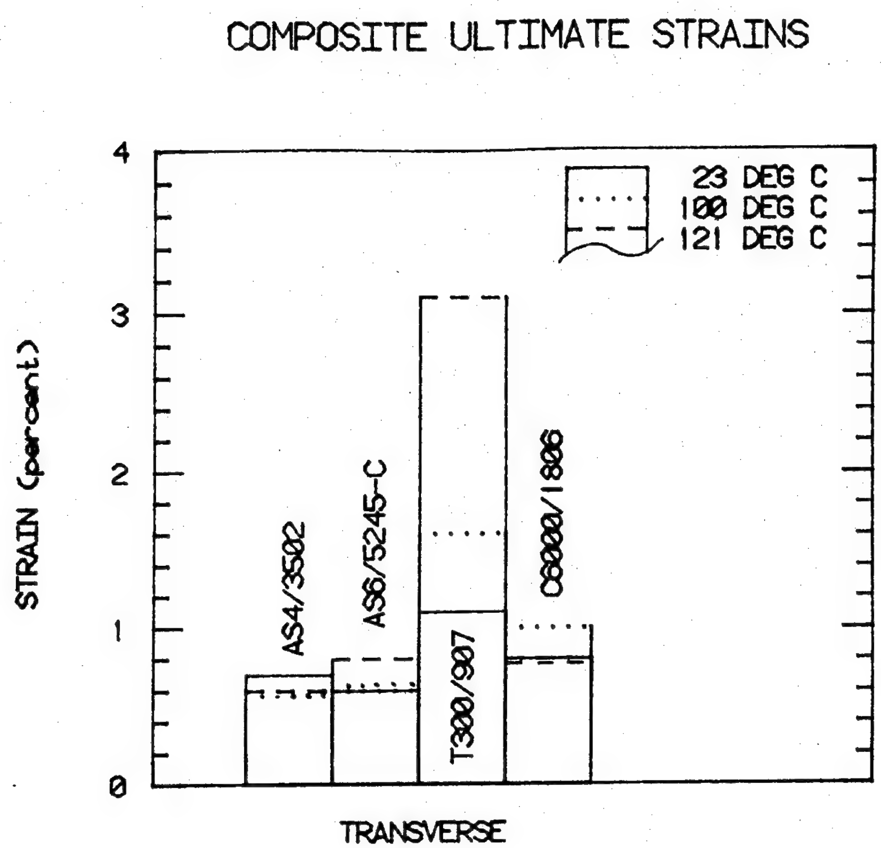

Figure 28. Unidirectional Carbon Fiber-Reinforced Composite Transverse Tensile Ultimate Strains.

Strains at the 100°C test condition remained similar to the 23°C values, except for the C6000/1806 and T300/BP907, which increased in magnitude slightly.

Average transverse tensile properties are given in Table 8. A third test temperature was added for the transverse tensile test configuration only, as indicated in Table 8. The testing at 121°C was done to provide additional data for this matrix-dominated configuration. The test data indicates that useful properties are maintained by all material systems except the T300/CYCOM 907 at the 121°C temperature.

5.5 <u>Composite In-Plane Shear Test Results</u>

Complete shear stress-shear strain curves to failure were recorded for all of the composite in-plane shear tests. Individual shear stress-shear strain curves and test results are given in Appendices A and B. Average in-plane shear properties are listed in Table 8. Figure 29 is a bar chart of in-plane shear strengths for the four carbon fiber-reinforced composites. Small differences are seen between the four composites at the room temperature condition but a much larger variance is seen at the 100°C test temperature. The T300/CYCOM 907 composite degraded to one-half of its original shear strength at the elevated temperature while the other three composites fell only about 20 percent from their room temperature shear strengths. In-plane shear is a matrix-dominated property and thus these results were expected after viewing the neat resin behavior. A typical failed shear specimen is shown in Figure 30. Note the displacement between the right and left halves of the specimen and the faint horizontal cracks between the notches, which are typical shear failure surfaces. The large horizontal

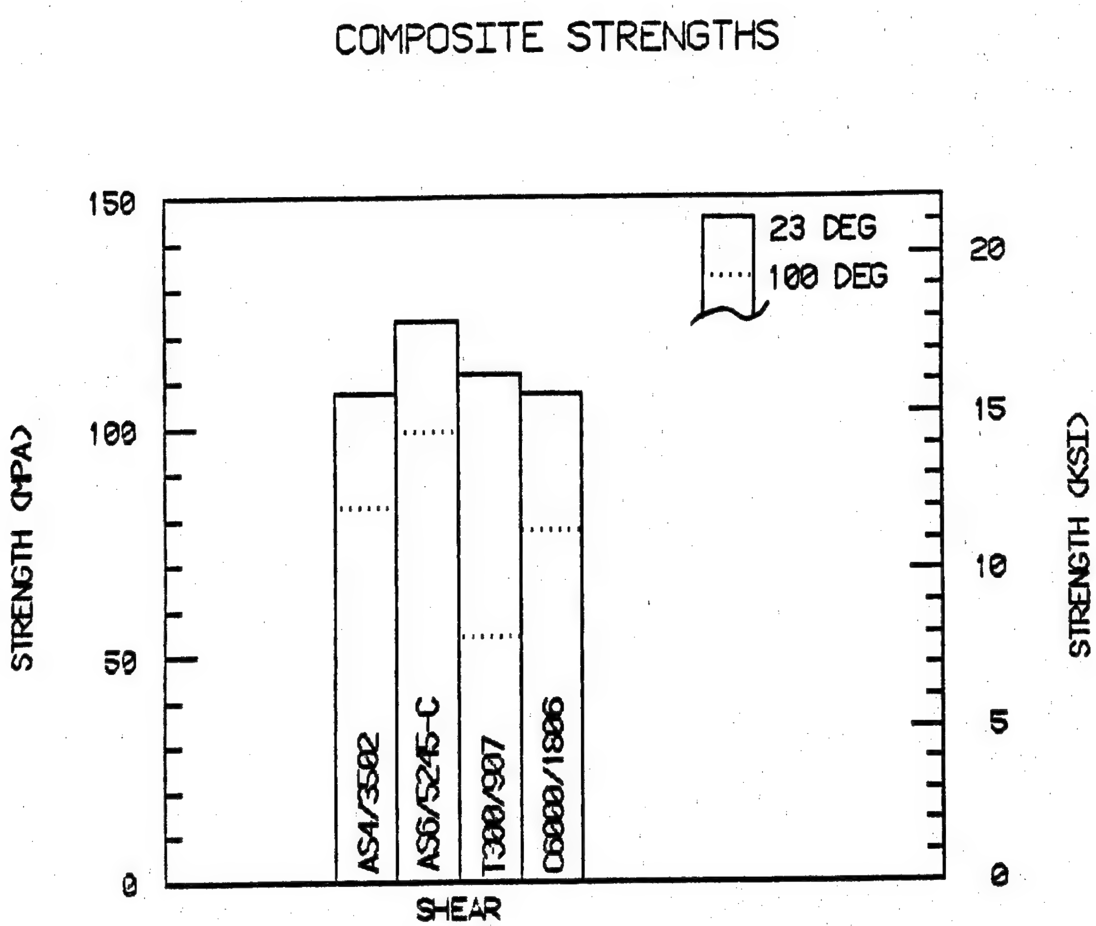

Figure 29. Unidirectional Carbon Fiber Reinforced Composite In-Plane Shear Strengths.

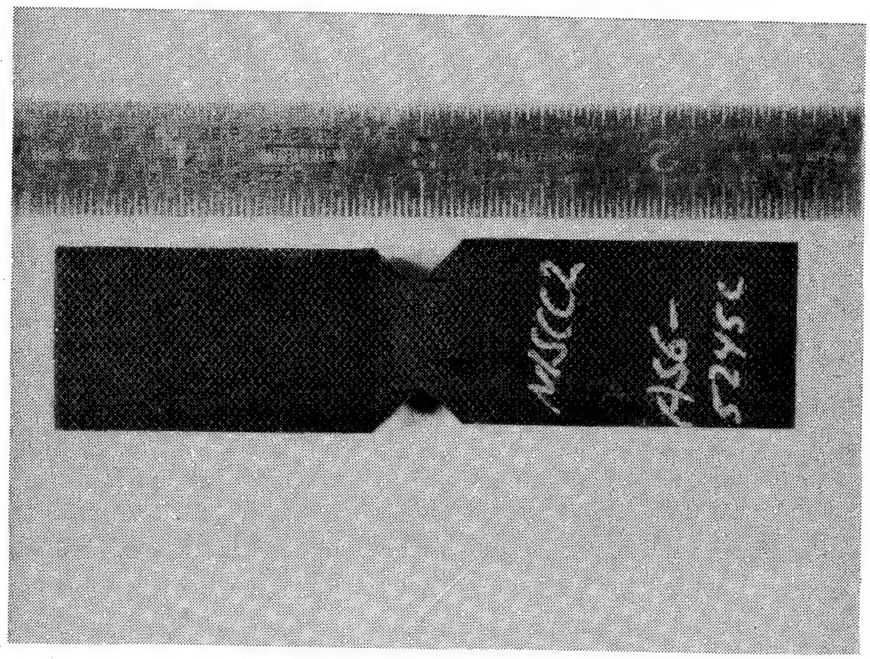

Figure 30. Typical Failed Iosipescu Shear Test Specimen.

cracks near the notches act as stress concentration dampeners and assist in maintaining a uniform shear strain field in the gage section [9].

Shear modulus values are presented in bar chart form in Figure 30. Only small differences are seen between the four materials at room temperature. The shear modulus tends to follow the axial tensile modulus, i.e., the higher axial tensile modulus materials having the higher shear modulus and conversely the materials with lower axial tensile moduli having the lower shear moduli. The elevated temperature shear modulus values were similar to the room temperature values for three of the composites, with the T300/CYCOM 907 material falling to only 25 percent of its room temperature value at 100°C. This dramatic degradation was also quite evident in the neat resin testing of this material.

The bar chart showing the ultimate shear strain values for the four composite materials is not shown due to calibration problems affecting shear strain values. The room temperature shear strain for the C6000/1806 is artificially low due to the strain gage calibration being set too low for the material. The lack of variation between the four materials shear strain in Table 8 is artificial due to full range strain gage limitations. The baseline matrix material for this multi-year study has been the Hercules 3502 epoxy. As can be seen, the corresponding component exhibited the lowest shear strain of the four composites at both environmental conditions. For three of the composites tested at the elevated temperature condition, the strain gage rosettes became saturated. Thus, only the shear strain of the AS4/3502 composite is a true ultimate since these specimens did fail before the strain gages failed. The AS6/5245-C and T300/CYCOM 907 composites

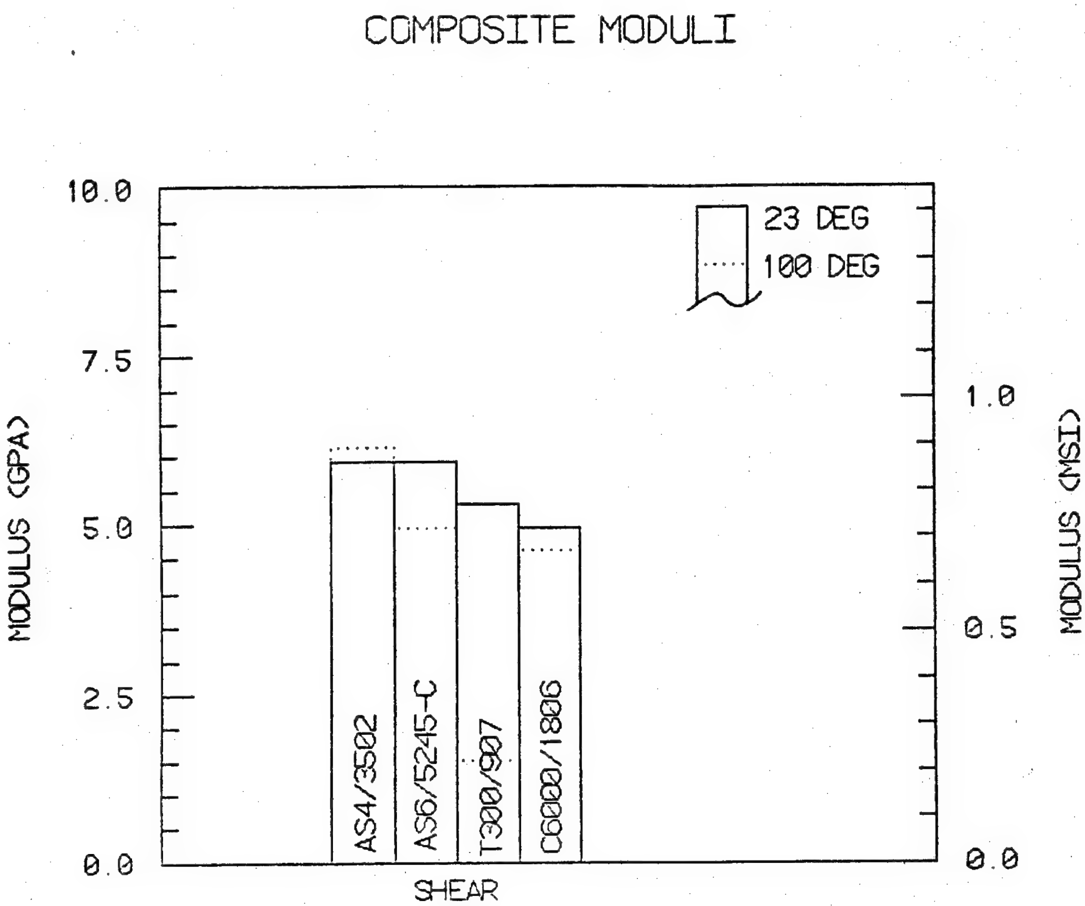

Figure 31. Unidirectional Carbon Fiber-Reinforced Composite In-Plane Shear Moduli.

exhibited high shear strain at room temperature as well with the specimens continuing to carry load after the strain gage rosette had failed.

The strain gages used were Measurements Group No. EA-13-062TV-350 shear gage rosettes. They are limited to 3 percent strain per gage or 6 percent total when wired in a half bridge as here. Higher elongation strain gages are available, to increase the ultimate strain capability to 10 percent strain per gage, i.e., 20 percent total. In the future, Measurements Group Gage No. EP-08-062TH-120 will be used for these higher strain capability applications, as materials continue to be developed which exhibit higher strains to failure.

5.6 Composite Transverse Coefficient of Thermal Expansion Tests Results

Transverse coefficient of thermal expansion tests were performed on all four composite material systems. Three of the composite materials behaved relatively linearly over the full temperature range. This resulted in a constant value of CTE for those three systems. Figure 32 is an example of the linear behavior of the AS4/3502 composite. Average curve-fit parameters for the four materials are listed in Table 16. Both thermal cycles are plotted as asterisks every 10°C, with the straight curve-fit line being drawn on top of the data points. The T300/CYCOM 907 composite behaved in a highly nonlinear manner, Figure 33 being an example. The top set of data points represents the first cycle. A drop-off in expansion is quite noticeable at the high temperature end. This drop-off was due to a shrinkage of the test specimen above 90°C. This was verified by measuring the specimens before and after testing and comparing the final length with the initial

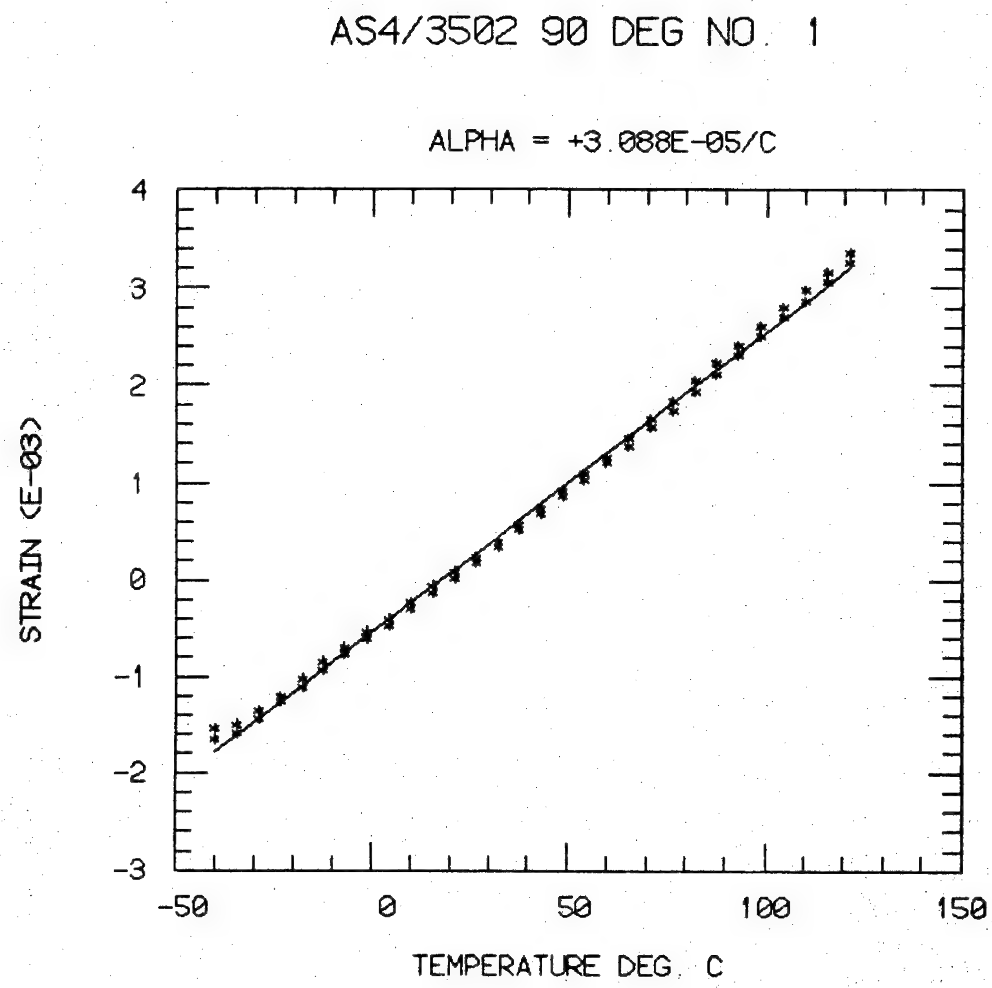

Figure 32. Typical Transverse Coefficient of Thermal Expansion Plot for the AS4/3502 Composite Including Both Sets of Temperature Cycle Data.

Table 16
Average Composite Transverse Thermal Expansion Test Results
$CTE = C_1 + C_2T \quad (10^{-6}/°C)$

Material System	Coefficients C_1	C_2
AS4/3502	30.8	0
AS6/5245-C	32.8	0
T300/907	30.4	0.196
C6000/1806	33.2	0

length. Table 17 shows the initial, final, and change in length for all composite CTE specimens. The significant shrinkage experienced by the T300/CYCOM 907 specimens will be noted. The C6000/1806 specimens exhibited a small length increase, but no effect of this was seen in the CTE data curves. The second thermal cycle data points are plotted as the lower row of asterisks. The initial slopes of the two cycles are similar, as shown on the plot. The second cycle data demonstrates a continuous smooth curve without any drop-off at the higher temperature portion of the test. This implies that the test specimens had stabilized after only one thermal cycle and that the second cycle curve is probably a better measure of actual material behavior. Figure 34 is the same T300/BP907 test (Figure 33) with only the second thermal cycle plotted. The values given in the data tables for this material are taken from only the second thermal cycle data points. Individual test results and test plots are given in Appendices A and B, respectively.

5.7 Composite Transverse Coefficient of Moisture Expansion Tests

Transverse coefficient of moisture expansion (CME) tests were also performed on the four carbon fiber-reinforced composites using the same test apparatus as used on the neat resin, and described in Section 3.3 and shown in Figure 5.

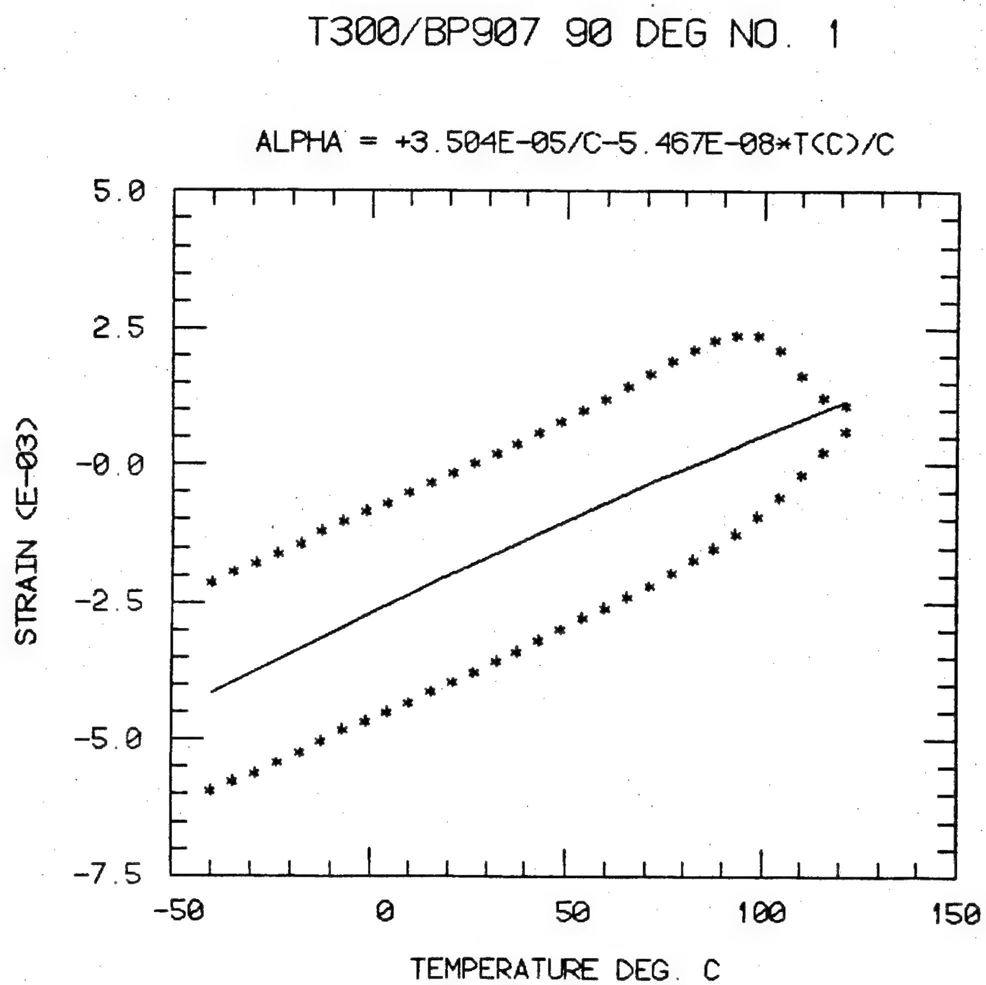

Figure 33. Typical Transverse Coefficient of Thermal Expansion Plot for the T300/BP907 Composite, Including Both Sets of Temperature Cycle Data.

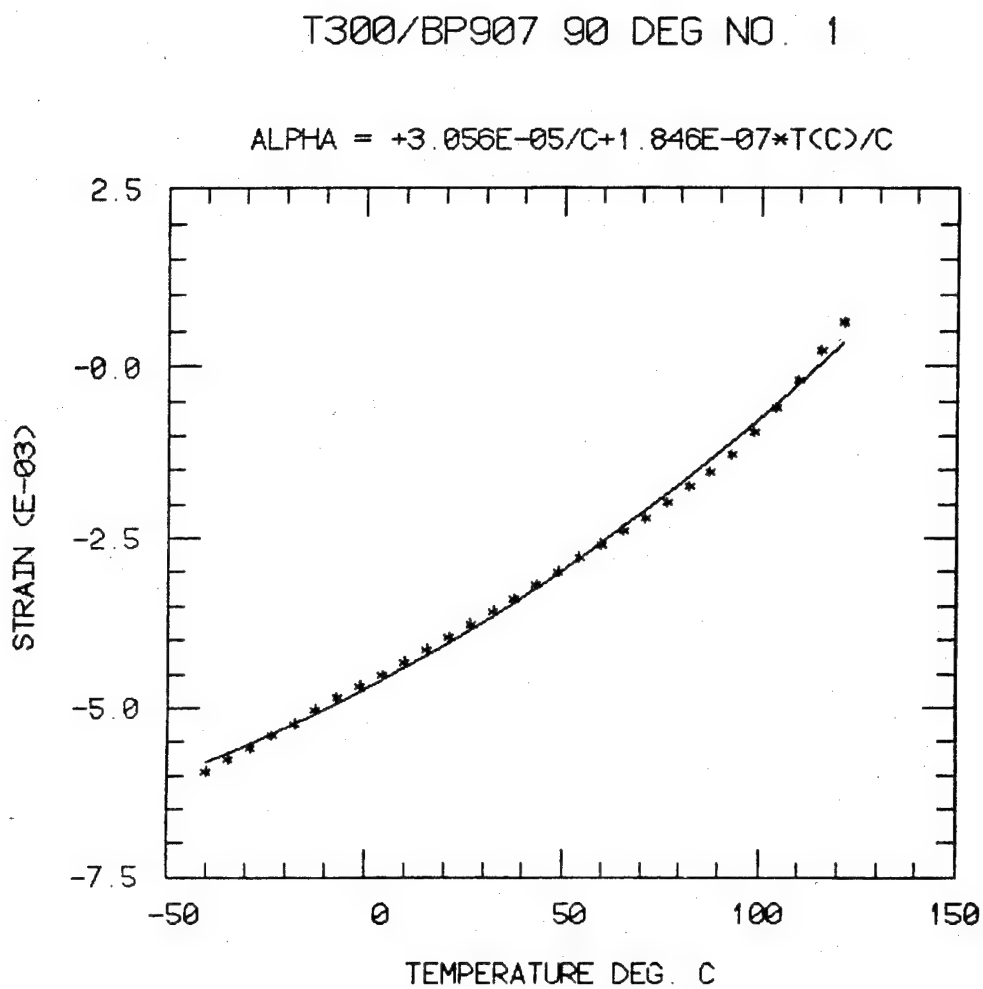

Figure 34. Transverse Coefficient of Thermal Expansion Curve for T300/BP907 Composite Showing Only the Second Cycle of the Test.

Table 17

Lengths of Individual Coefficient of Thermal Expansion Specimens Before and After Testing

Material System	Specimen No.	Initial Length (in)	Final Length (in)	Change in Length (in)
AS4/3502	1	5.106	5.106	0.000
	2	5.107	5.106	-0.001
	3	5.107	5.108	+0.001
AS6/5245-C	1	5.104	5.105	+0.001
	2	5.104	5.104	0.000
	3	5.105	5.105	0.000
T300/907	1	5.115	5.098	-0.017
	2	5.119	5.099	-0.020
	3	5.118	5.098	-0.020
C6000/1806	1	5.125	5.129	+0.004
	2	5.135	5.141	+0.006
	3	5.130	5.135	+0.005

The slopes of the transverse strain vs moisture curves for the composites were typically constant; the average coefficient of moisture expansion values are presented in Table 18. These are averages of three to six individual tests per material. Individual CME values are given in Appendix A. Plots for individual test specimens are given in Appendix B.

Table 18
Average Composite Transverse Moisture Expansion Coefficient Test Results

Material System	Transverse CME (10^{-3}/%M)
AS4/3502	4.67
AS6/5245-C	4.02
T300/907	2.59
C6000/1806	2.83

SECTION 6

SCANNING ELECTRON MICROSCOPY

4.1 Introduction

Scanning electron microscopy (SEM) was performed on selected failed neat resin test specimens. The Composite Materials Research Group (CMRG) has utilized the SEM for many years to study both composite material fractures and unreinforced (neat) resin fractures. The SEM provides a large depth of field at high magnification and is thus much more useful in the study of the rough fracture surfaces seen in neat resins than the optical microscope. A JEOL-35C scanning electron microscope was used for all of the work of this present study. This unit has a magnification range from 10X to 180,000X, a depth of field of 30μ at 1000X, and a resolution of 60Å. Magnifications between 10X and 500X are particularly informative when examining neat resin fractures, although higher magnifications (up to 5000X) are sometimes useful.

4.2 Specimen Preparation

Representative failed specimens were mounted for examination to show the representative failure features for the two neat resins studied. A large number of photographs were also taken during the first and second years of the present study [1,2], which provide a good detailed data base for studying neat resin failure surfaces. Similar features were seen again this year in the two neat resins observed. Only a small number of SEM photographs will be presented here due to the similarity in surface features.

Specimens were cut from failed neat resin specimens using a Bueller No. 4150 silicon carbide abrasive cutoff blade. All SEM specimens were then cleaned in an ultrasonic cleaning tank to remove any surface debris. Duco cement was used to bond the specimens to the 25.4 mm diameter brass mounting disks. Silver conducting paint was then applied between the brass disk and specimens along the bond line to ensure a good conducting path between the two. Gold was then vapor-deposited on all specimens to make them electrically conductive and prevent the accumulation of electrons on the fracture surface during the SEM viewing. Any accumulation of electrons on the surface of a specimen, when exposed to the high energy electron beam, causes flaring and hence a poor viewing image.

4.3 Explanation of SEM Photographs

Failed specimens representing several test conditions for each resin type were viewed and photographed. A brief description of each SEM photograph is given below each figure.

The SEM records information directly across the bottom of each photograph. Referring to Figure 35 as an example, the caption reads: 25 KV X15 2201 1000.OU UW 85. The interpretation is as follows:

25 KV	Electron beam accelerating voltage, in kilovolts
X15	Magnification
2201	Photograph number
1000.OU	Length of scale bar, in microns
UW 85	The SEM unit identification number, i.e., University of Wyoming and the current year, 1985.

The specimen numbering system is summarized here for convenience.

A typical specimen name is divided into four sets of characters. For example, the specimen number in Figure 35 is NTAAD5. This is interpreted as follows:

N	identifies the program, NASA-Langley neat resin testing.
T	identifies type of mechanical test.
A	identifies resin system.
A	identifies test temperature.
D	identifies moisture condition.
5	identifies the specimen number.

The complete set of codes for all specimens tested is as follows:

Type of Mechanical Test

T Tension
S Torsional Shear
F Fracture Toughness

Resin System

A 1806
B ERX-4901B(MPDA)

Test Temperature

A 23°C
B 82°C
C 121°C
D 60°C
E 100°C

Specimen Conditioning

D Dry
W Moisture-Saturated

Specimen Number

1-9

This code is different from those used in the previous two studies. From five to nine specimens were tested at each condition. The two additional temperatures, 60° and 100°C were used for the ERX-4901B(MPDA) epoxy since it degraded to such a high degree above these temperatures.

4.4 Neat Resin Tension

Failed specimens were studied for the two neat resin systems at each test condition. Similar fracture surfaces as seen previously [1,2] were seen in the neat resins studied during the present year. A failure initiation site could be identified in most cases, located in the smooth zone of the fracture. A transition zone surrounded the smooth zone of the fracture becoming a rough area which is thought to be the last region to fracture at failure. Descriptions are give at the bottom of each photograph directly under the figure caption to allow viewing the photograph while reading the description.

4.5 Neat Resin Shear

Failed specimens were studied in the SEM for each test condition. Features were similar to those seen in the previous studies [1,2]. A swirl pattern was evident overall with surfaces being similar to the tension fracture surfaces.

4.6 Neat Resin Fracture Toughness

One specimen at each test condition was viewed and photographed to identify surface features characteristic of the two neat resins studied. Many of the fracture surfaces were smooth with little evidence of crack arrest being seen. This was predominant in many of the specimens indicating unstable crack growth in these specimens. Unstable crack growth is one indication of a brittle material.

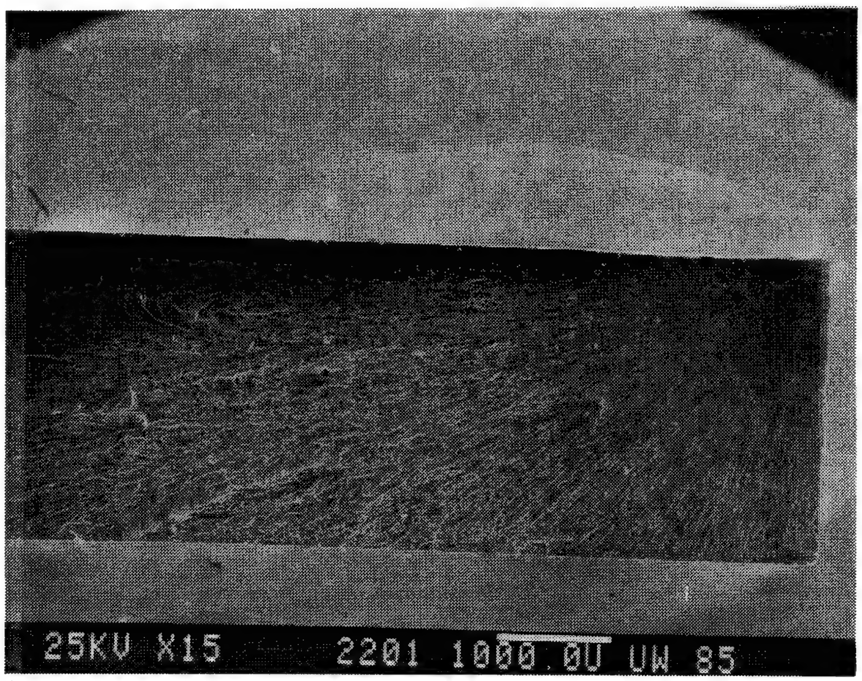

Figure 35. Overall Photograph of 1806 Epoxy Tension Specimen NTAAD5, 23°C, Dry Condition.

Failure initiation zone is at upper right corner progressing to the left.

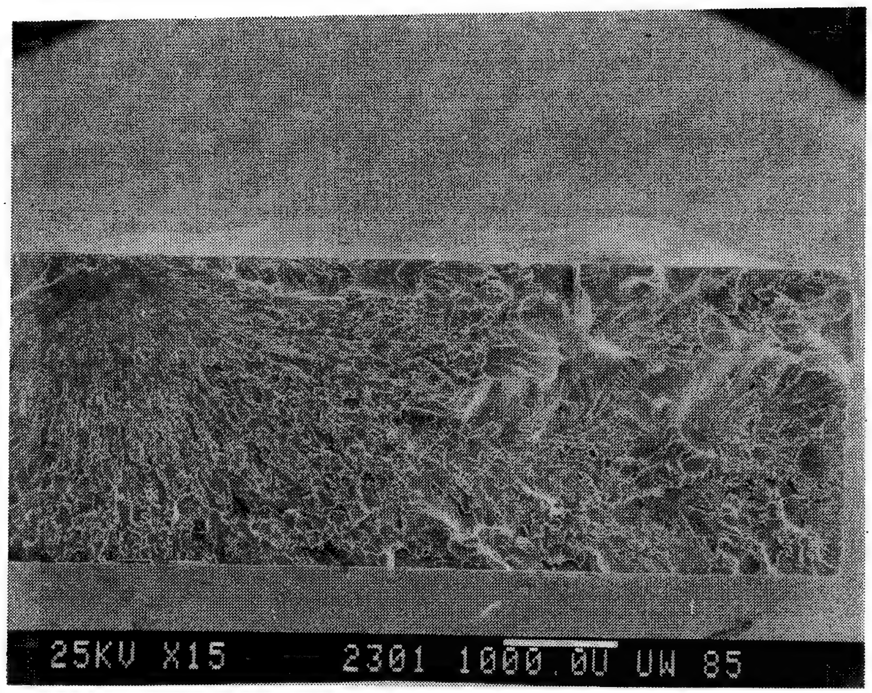

Figure 36. Overall Photograph of 1806 Epoxy Tension Specimen NTABD5, 82°C, Dry Condition.

Failure initiation zone is at upper left near the surface. Rough zone is more predominant compared to the 23°C test temperature in Figure 35.

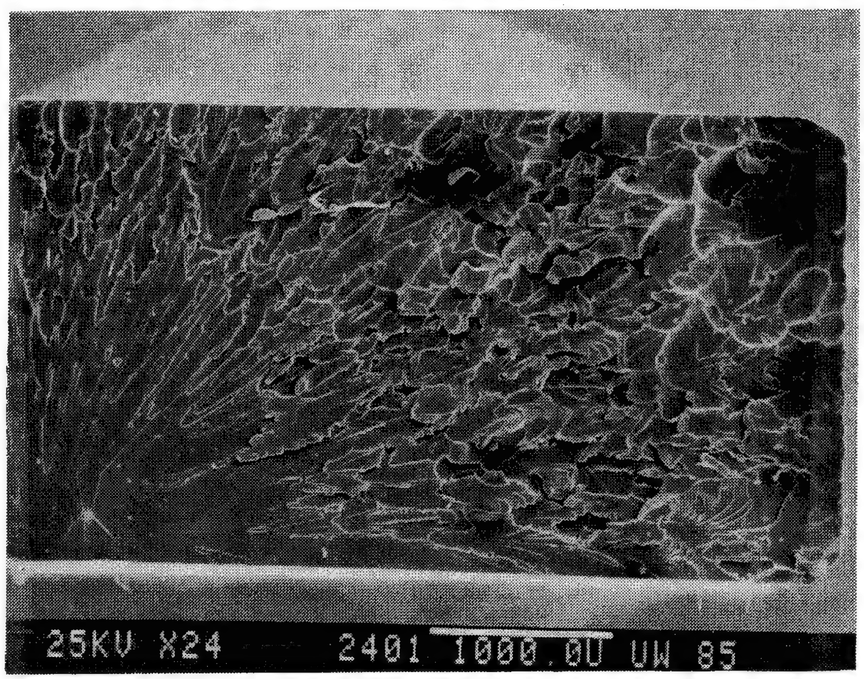

Figure 37. Overall Photograph of 1806 Epoxy Tension Specimen NTACD2, 121°C, Dry Condition.

Fracture initiated at void in lower left corner with a much coarser surface than the lower temperature specimens.

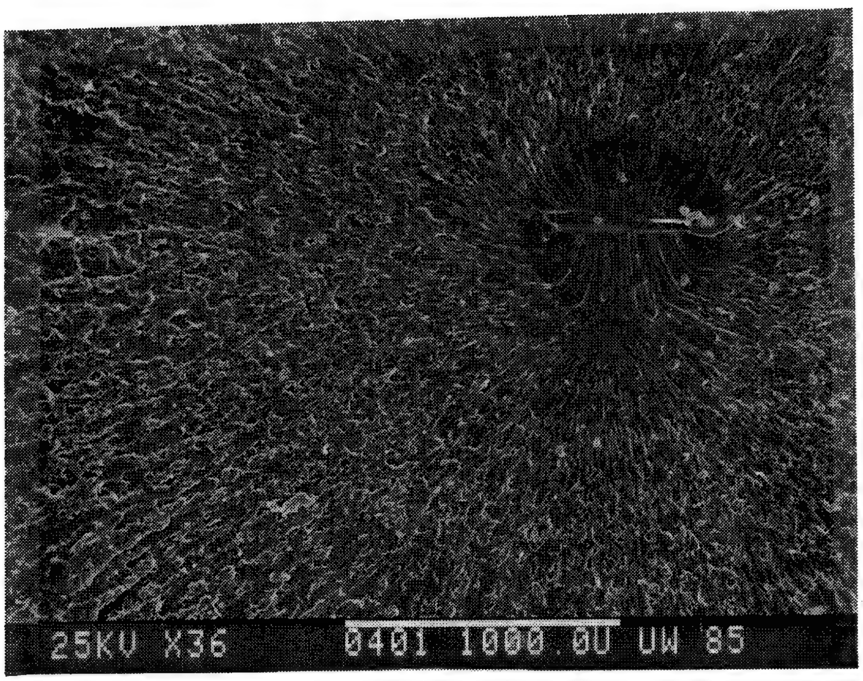

Figure 38. Close-up Photograph of 1806 Epoxy Tension Specimen NTAAW3 23°C, Moisture-Saturated.

Showing failure initiation point and surrounding area. An elongated void region appears to have been the location for this failure.

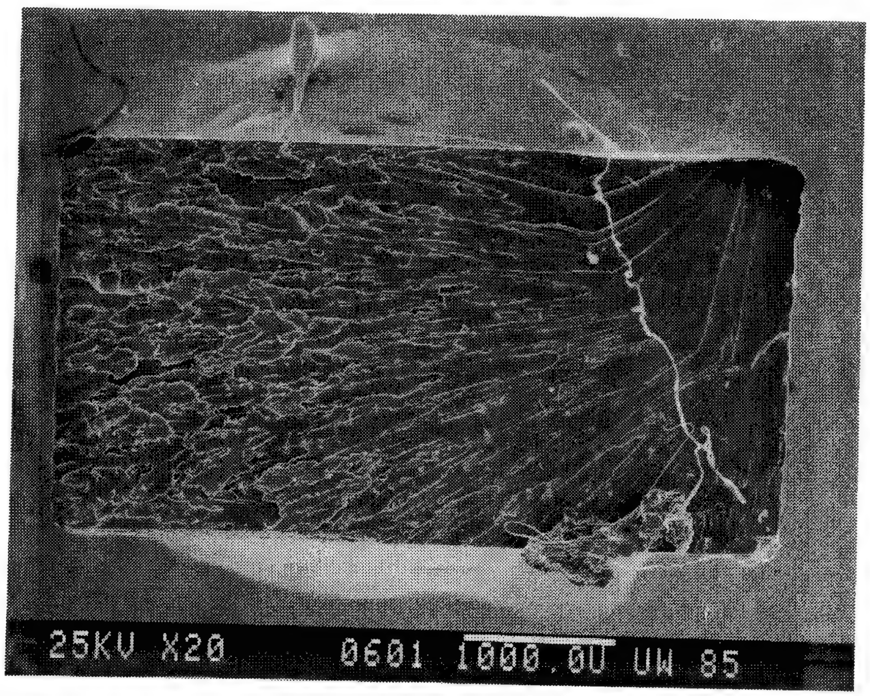

Figure 39. Overall Photograph of 1806 Epoxy Tension Specimen NTAAW3, 82°C, Moisture-Saturated.

The failure began in upper right corner and progressed to the left across the specimen.

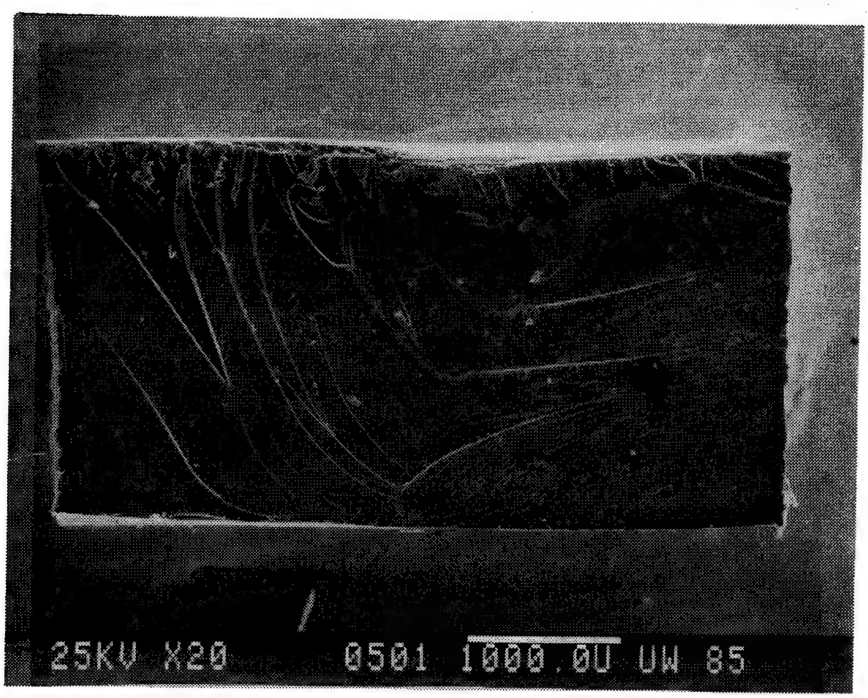

Figure 40. Overall Photograph of 1806 Epoxy Tension NTACW4, 121°C, Moisture-Saturated.

This fracture surface is quite smooth and atypical for neat resin failures.

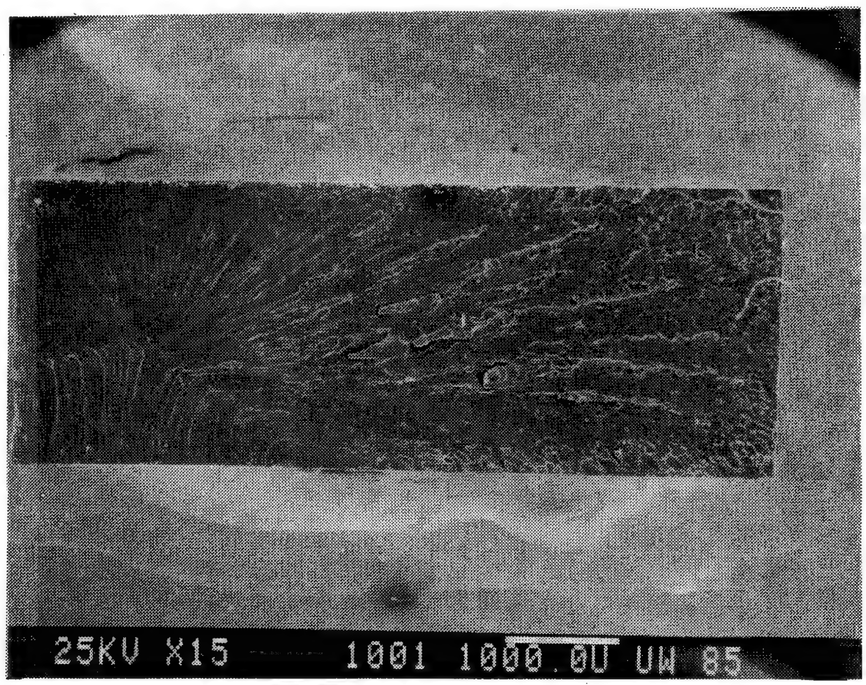

Figure 41. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBAD6, 23°C, Dry Condition.

Fracture surface is smoother than most failures with initiation point at center left.

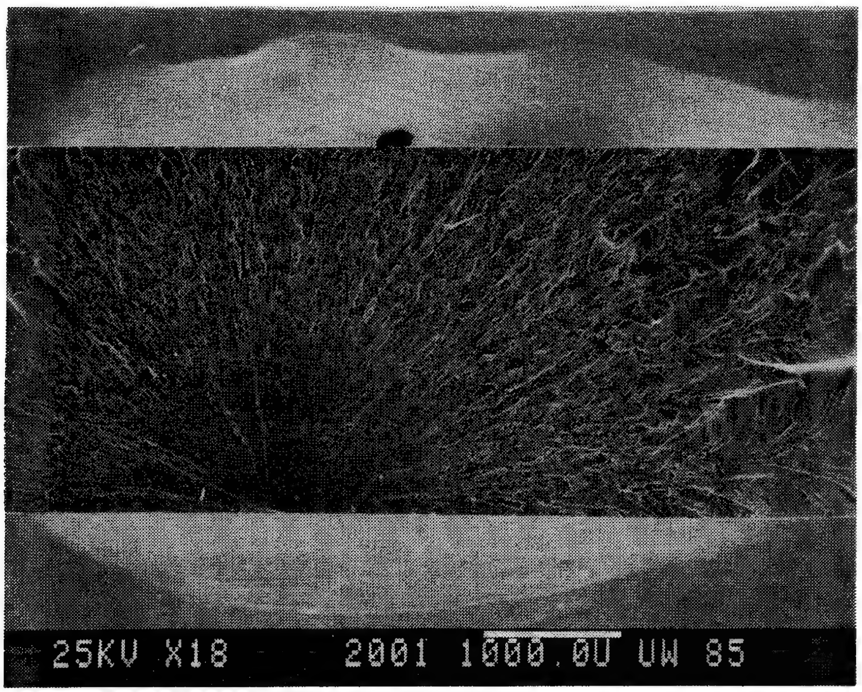

Figure 42. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBBD6, 82°C, Dry Condition.

Very typical failure surface for neat resin fractures with three zones apparent.

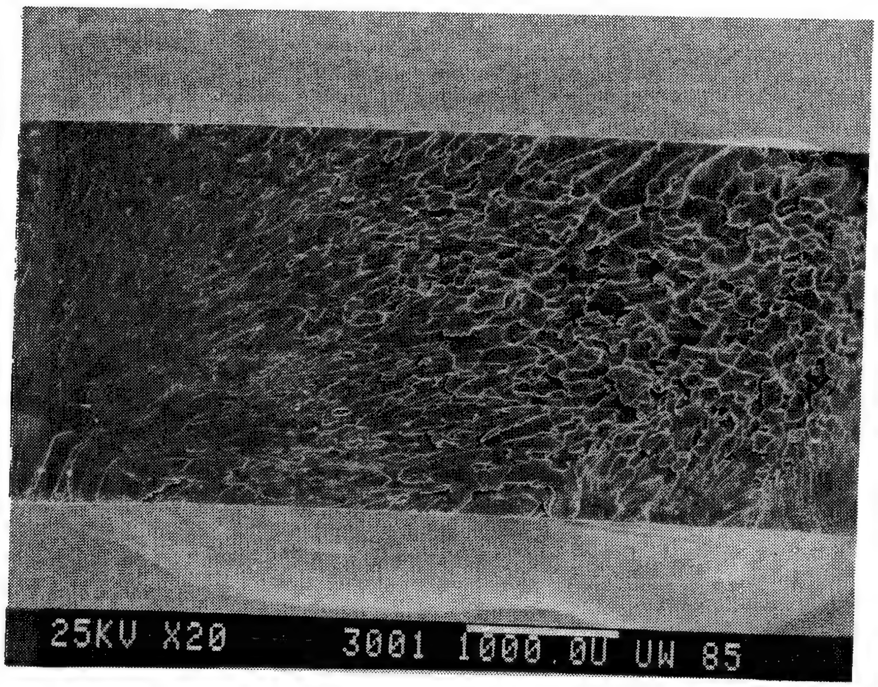

Figure 43. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBCD1, 121°C, Dry Condition.

Typical fracture surface for neat resin with initiation at lower left cover and rough area to right.

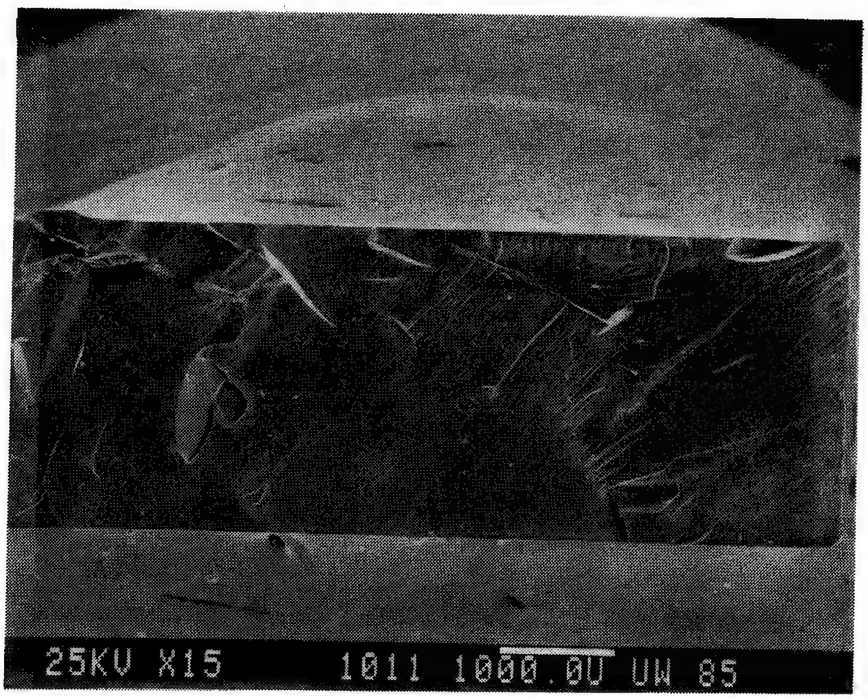

Figure 44. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBAW9, 23°C, Moisture-Saturated.

Very smooth fracture surface which indicates a brittle failure.

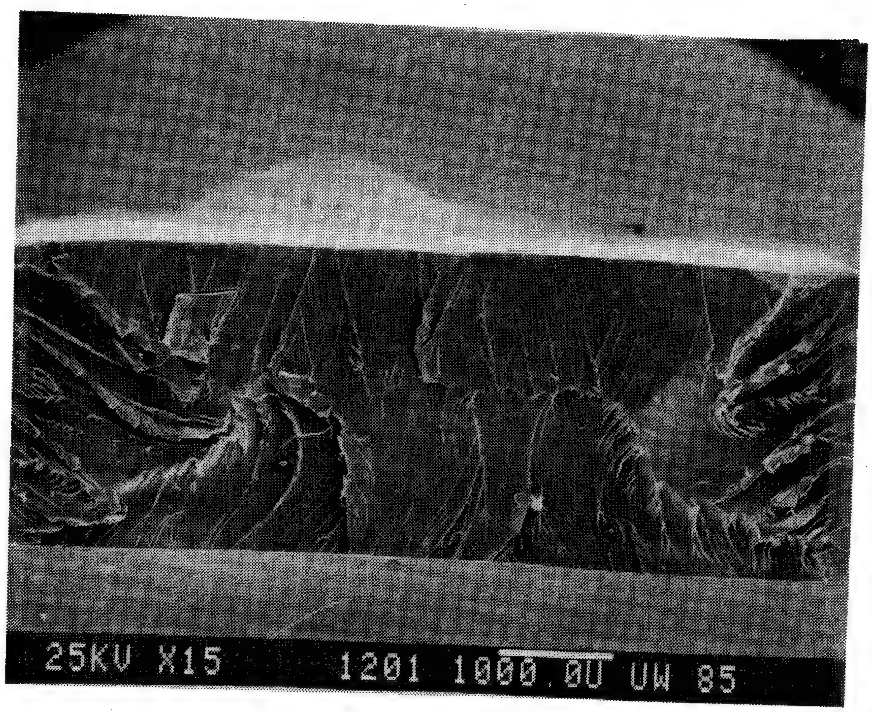

Figure 45. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBDW4, 60°C, Moisture-Saturated.

Much rougher surface over all the fracture surface. Three zones are not apparent in this specimen. Moisture plasticizing of the resin seems to have changed the fracture surface features and failure mode.

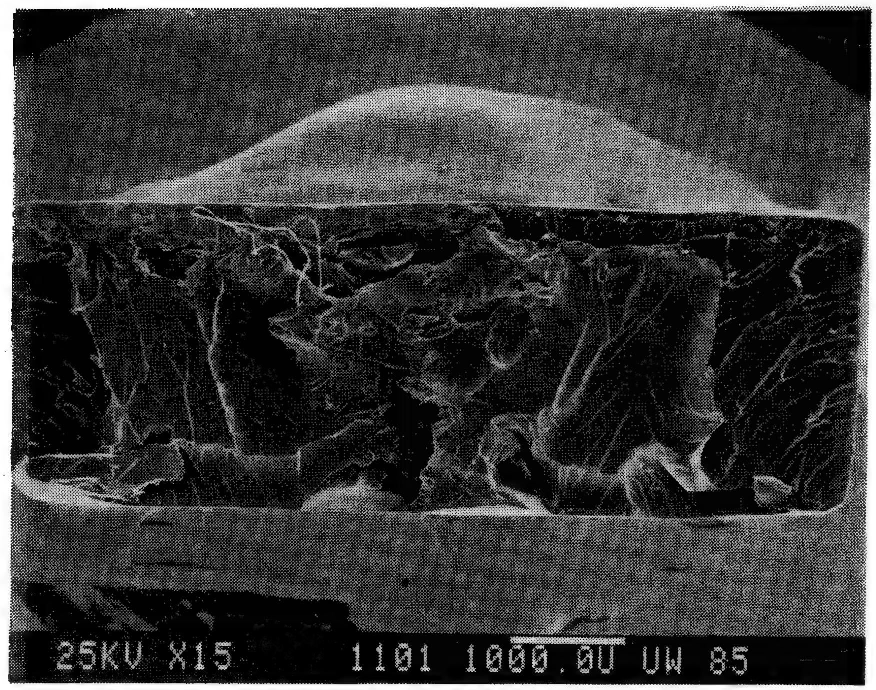

Figure 46. Overall Photograph of ERX-4901B Epoxy Tension Specimen NTBBW1, 82°C, Moisture-Saturated.

Extremely rough surface is seen here due to the plasticizing effect on the resin by water absorption.

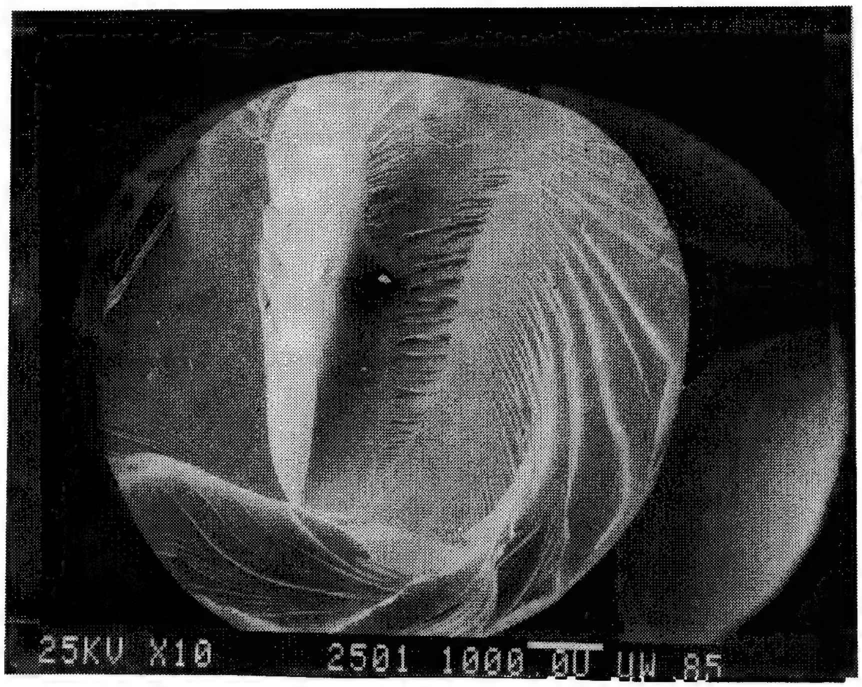

Figure 47. Overall Photograph of 1806 Epoxy Shear Specimen NSAAD5, 23°C, Dry Condition.

The smooth surface indicates a brittle failure at this test condition.

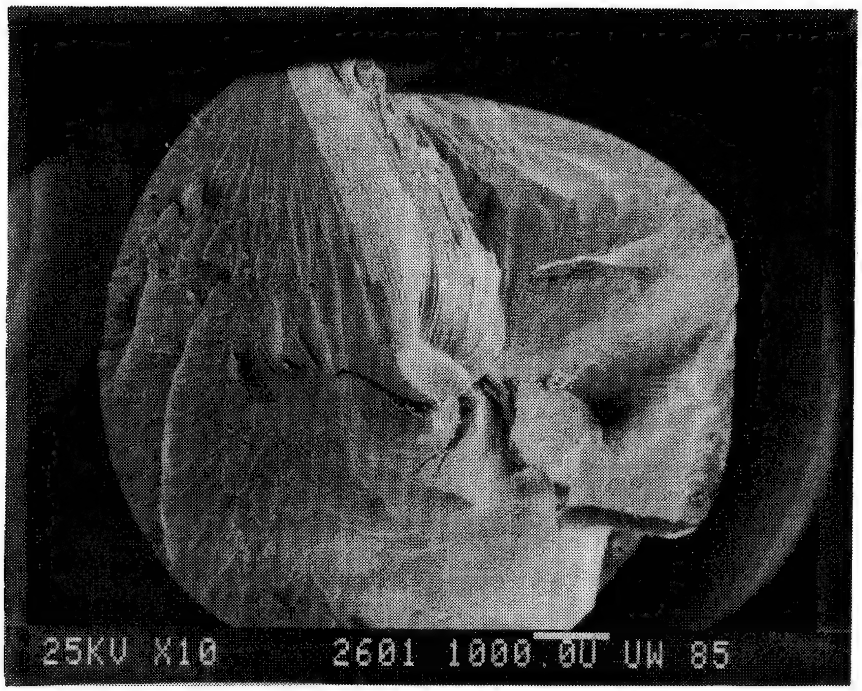

Figure 48. Overall Photograph of 1806 Epoxy Shear Specimen NSABD4, 82°C, Dry Condition.

This failure is much more typical with the initiation point at the top left and progressing inward.

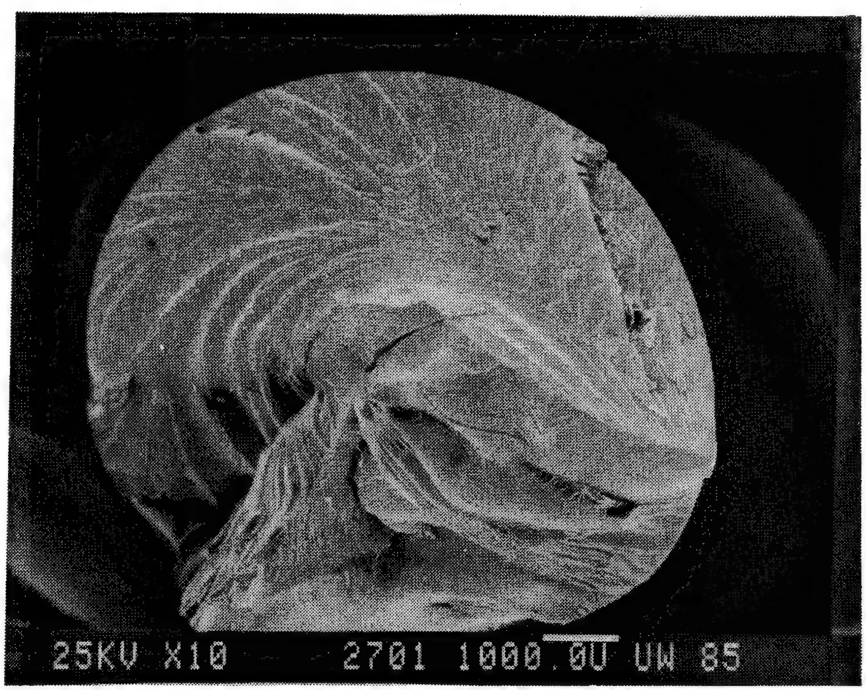

Figure 49. Overall Photograph of 1806 Epoxy Shear Specimen NSACD5, 121°C, Dry Condition.

This failure is somewhat more coarse than the lower temperature failures with more swirl appearance.

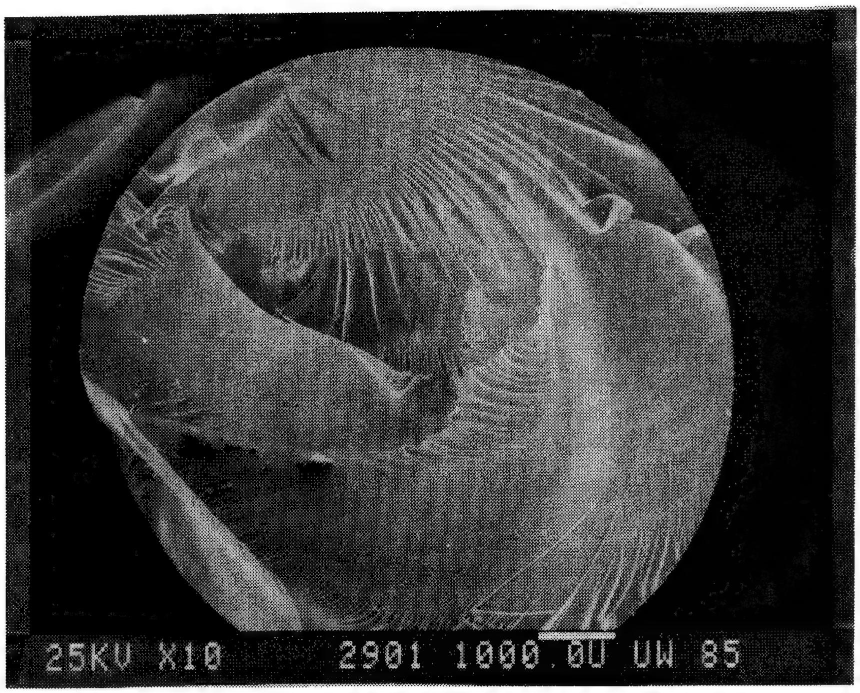

Figure 50. Overall Photograph of 1806 Epoxy Shear Specimen NSAAW5, 23°C, Moisture-Saturated.

Failure initiation began at the top center of the photograph with the swirl pattern extending away from it. The fracture surface is relatively smooth.

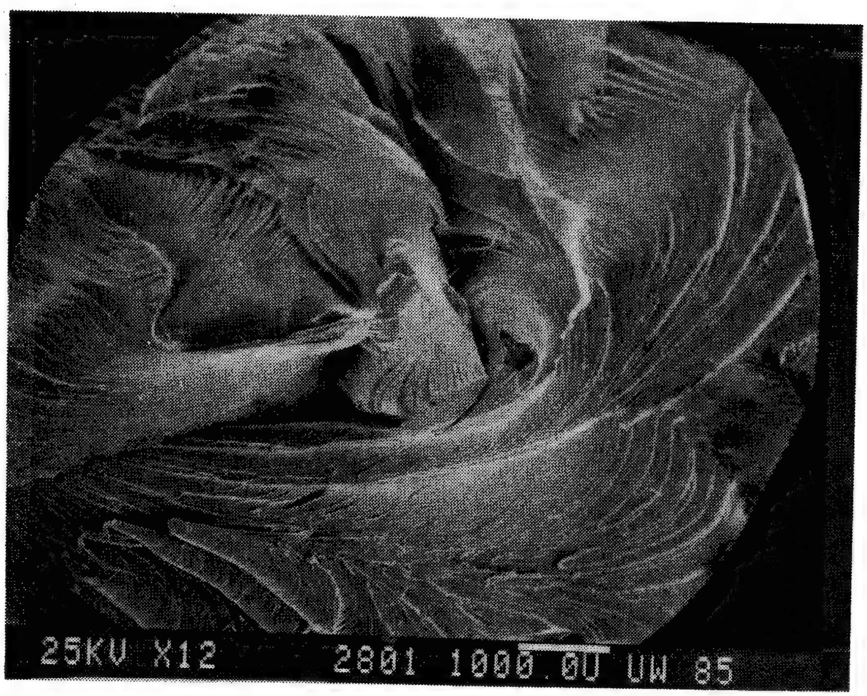

Figure 51. Overall Photograph of 1806 Epoxy Shear Specimen NSABW5, 82°C, Moisture-Saturated.

This failure surface is quite coarse which is indicative of higher temperature and/or moisture absorption.

Figure 52. Overall Photograph of 1806 Epoxy Shear Specimen NSACW4, 121°C, Moisture-Saturated.

This failure has a deep swirl that looks like a circular staircase in overall shape at the top of the photograph.

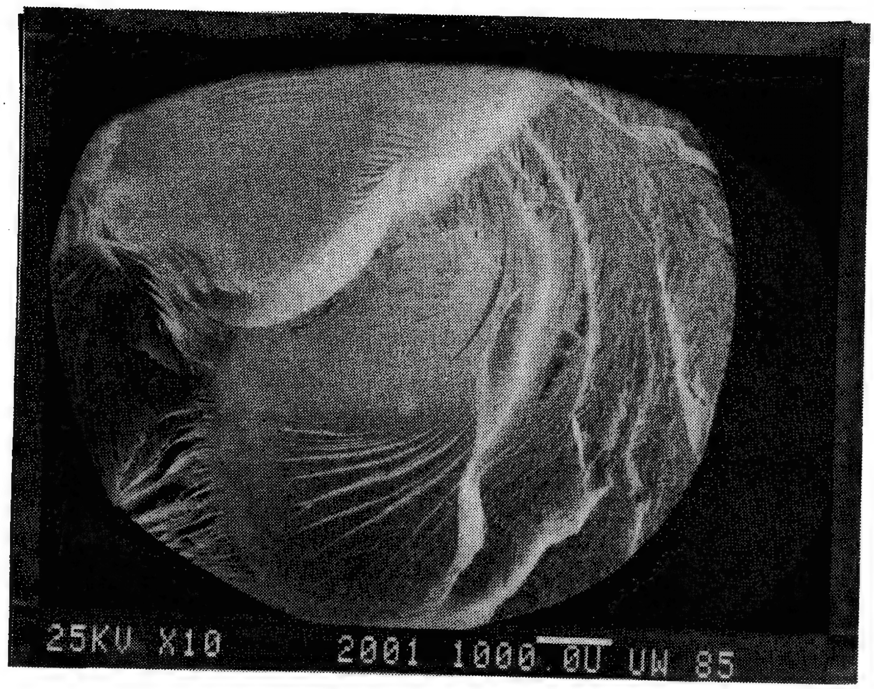

Figure 53. Overall Photograph of ERX-4901B(MPDA) Shear Specimen NSBAD4, 23°C, Dry Condition.

Surface at right is part of transition zone with the smooth surface at the left caused by the explosive nature of the failure and the brittle nature of the material.

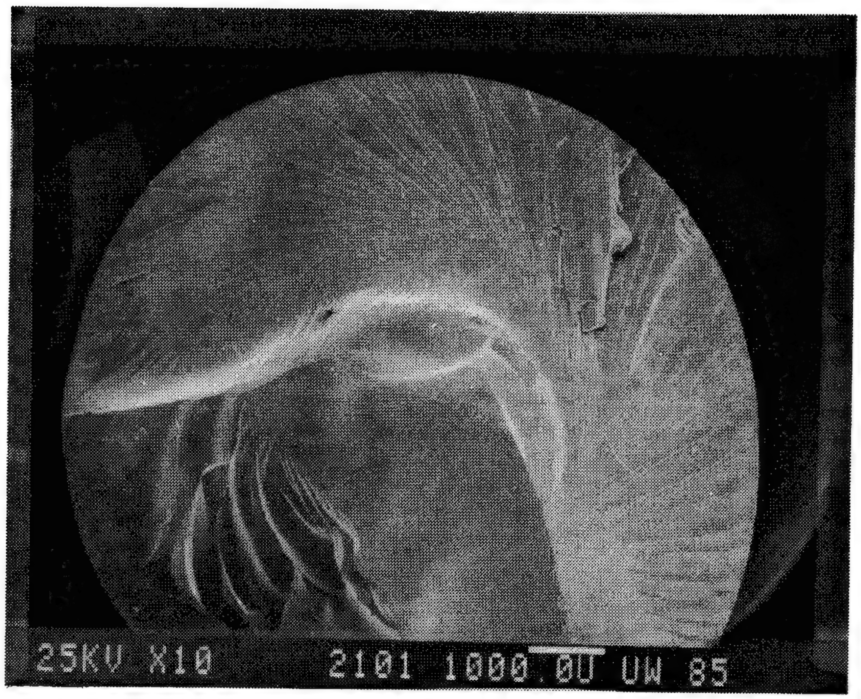

Figure 54. Overall Photograph of ERX-4901B(MPDA) Shear Specimen NSBBD1, 82°C, Dry Condition.

Failure surface is relatively smooth with some evidence of the transition zone at the left and top of the photograph.

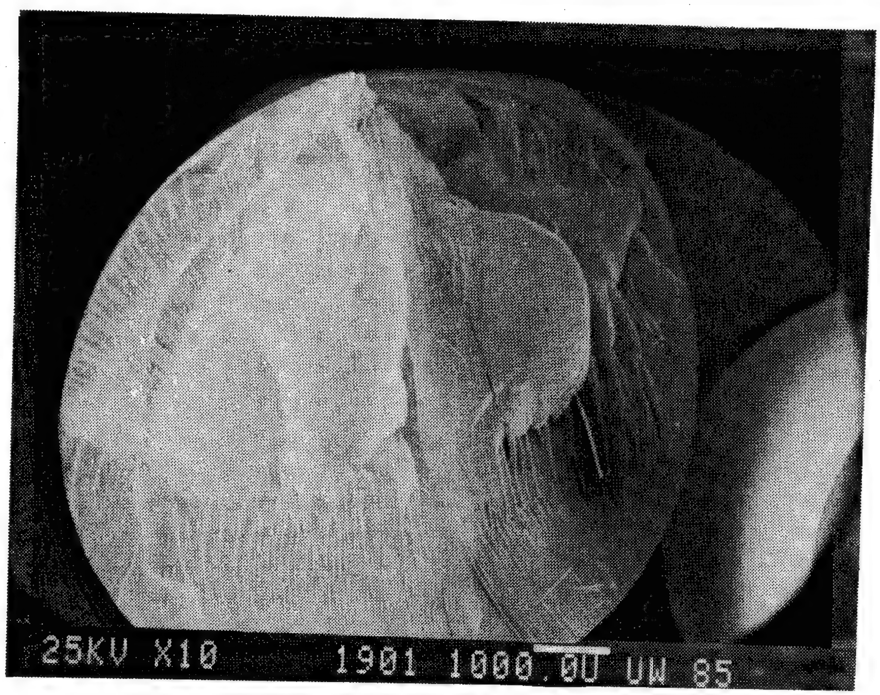

Figure 55. Overall Photograph of ERX-4901B(MPDA) Shear Specimen NSBCD4, 121°C, Dry Condition.

Circular striations are evident around the circumference of the specimen.

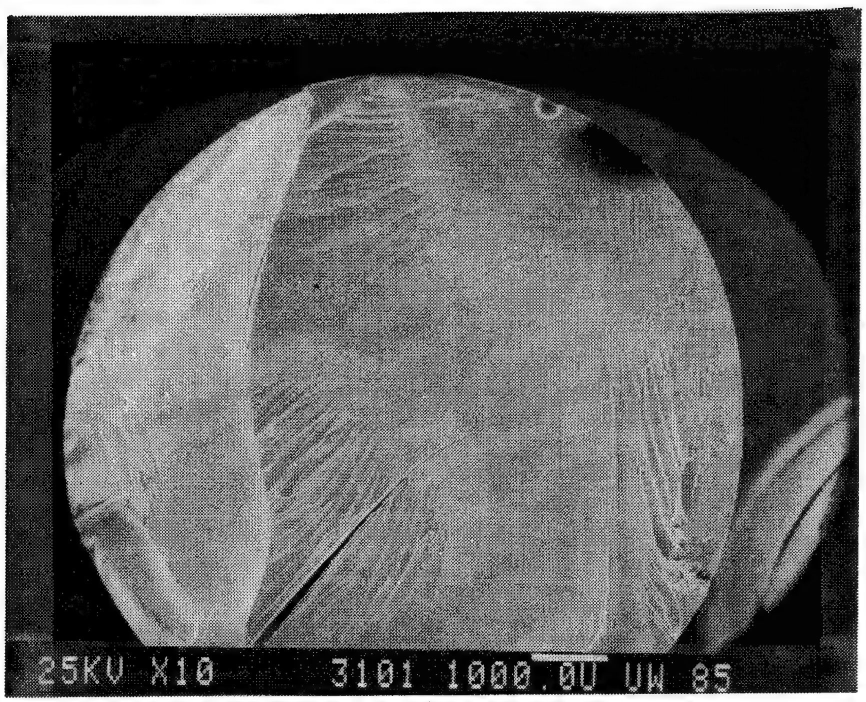

Figure 56. Overall Photograph of ERX-4901B(MPDA) Shear Specimen NSBAW2, 23°C, Moisture-Saturated.

This failure began at the top right of the photograph near the surface and propagated radially from that point inward.

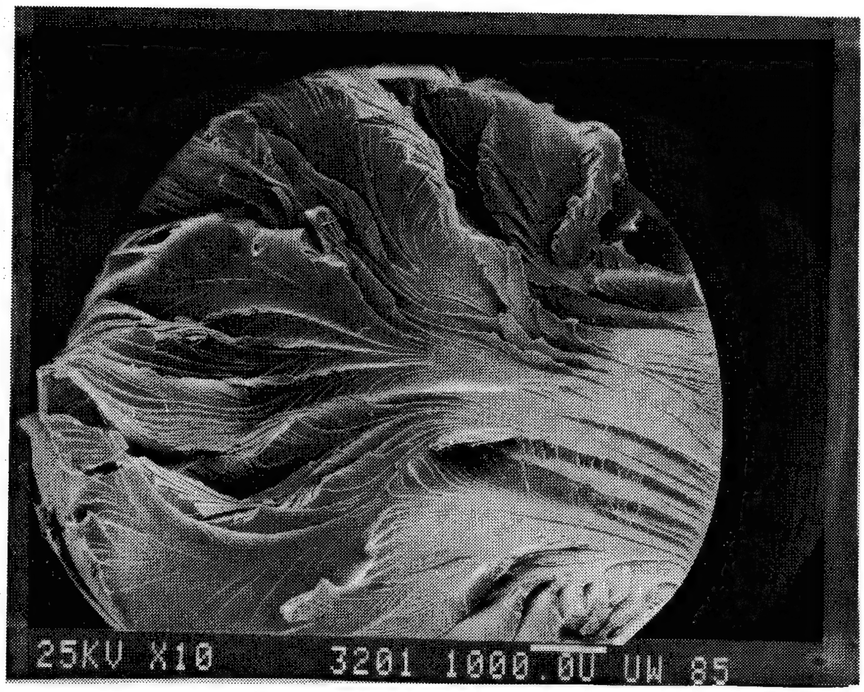

Figure 57. Overall Photograph of ERX-4901B(MPDA) Shear Specimen NSBBW2, 82°C, Moisture-Saturated.

The extremely coarse surface seen here is indicative of moisture plasticization and elevated temperature. Similar coarseness was evident in the tensile failures for this material at similar preconditioning and test conditions.

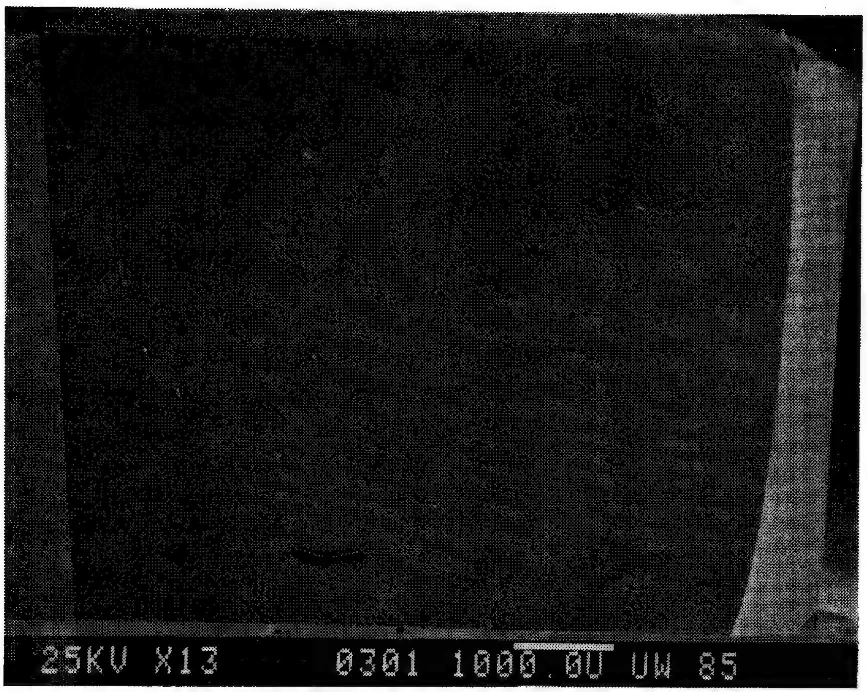

Figure 58. Overall View of 1806 Fracture Specimen NFAAD5, 23°C, Dry Condition.

Cut notch is at left margin with small striations evident. No evidence of crack arrest is evident at this test condition.

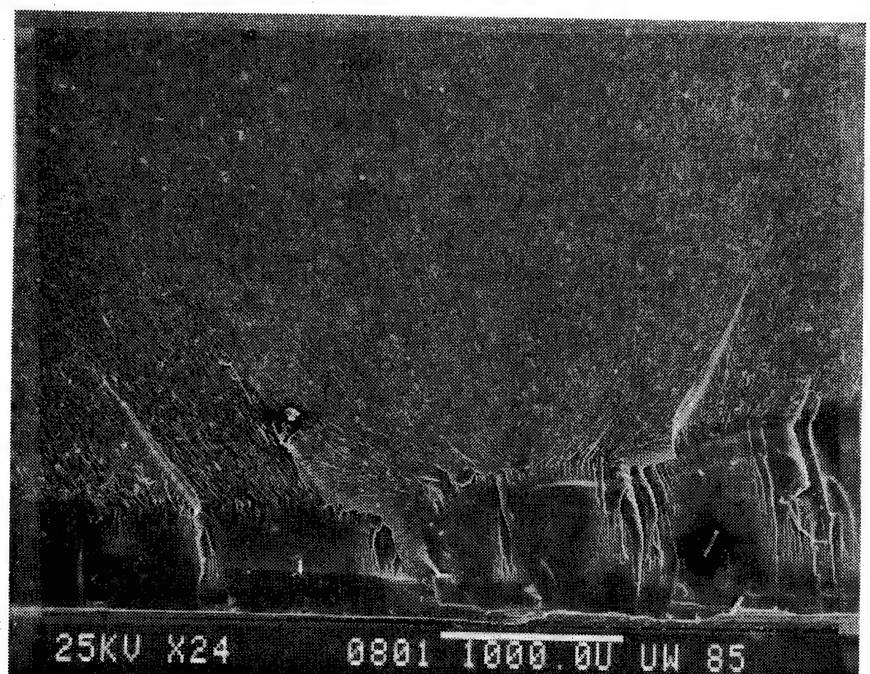

Figure 59. Close-up Photograph of 1806 Fracture Specimen NFABD8, 82°C, Dry Condition.

Cut notch is at bottom of photograph. The smooth section of the fracture changes quickly to the rougher transition zone with no evidence of a ridge which would indicate a crack arrest.

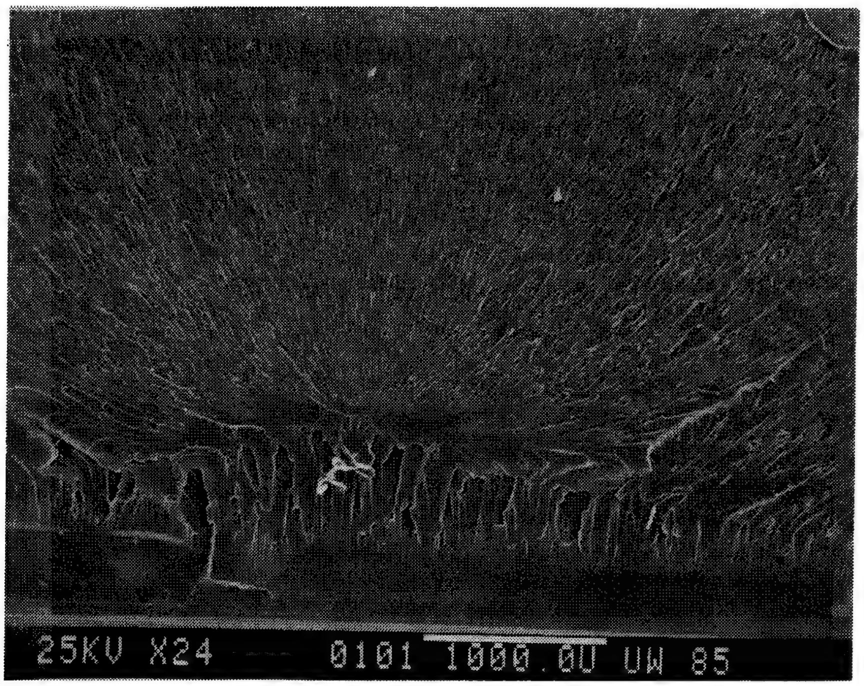

Figure 60. Close-up of 1806 Fracture Specimen NFACD6, 121°C, Dry Condition.

Cut notch is at bottom of photograph with the coarseness increasing at the higher test temperature.

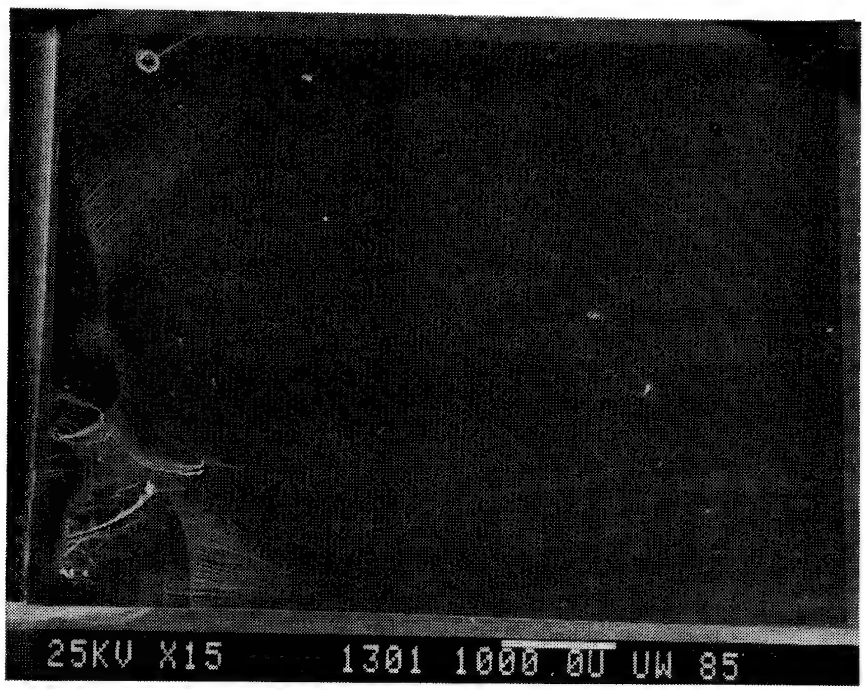

Figure 61. Overall Photograph of 1806 Fracture Specimen NFAAW11, 23°C, Moisture-Saturated.

Cut notch is at left edge of photograph.

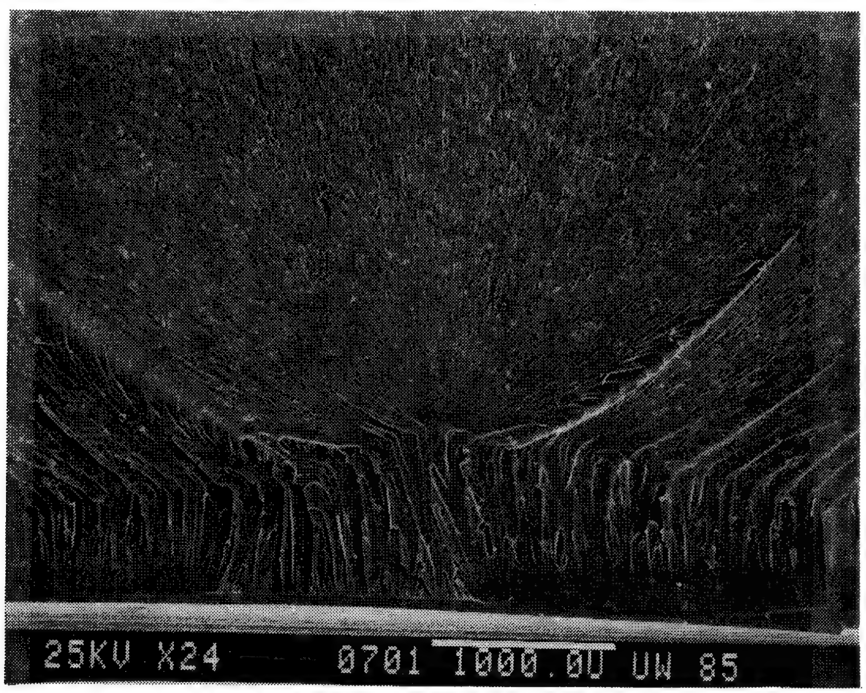

Figure 62. Close-up Photograph of 1806 Fracture Specimen NFABW2, 82°C, Moisture-Saturated.

Cut notch is at the bottom edge of the photograph. A much coarser surface is evident at this elevated temperature and after added moisture similar to a tensile fracture surface.

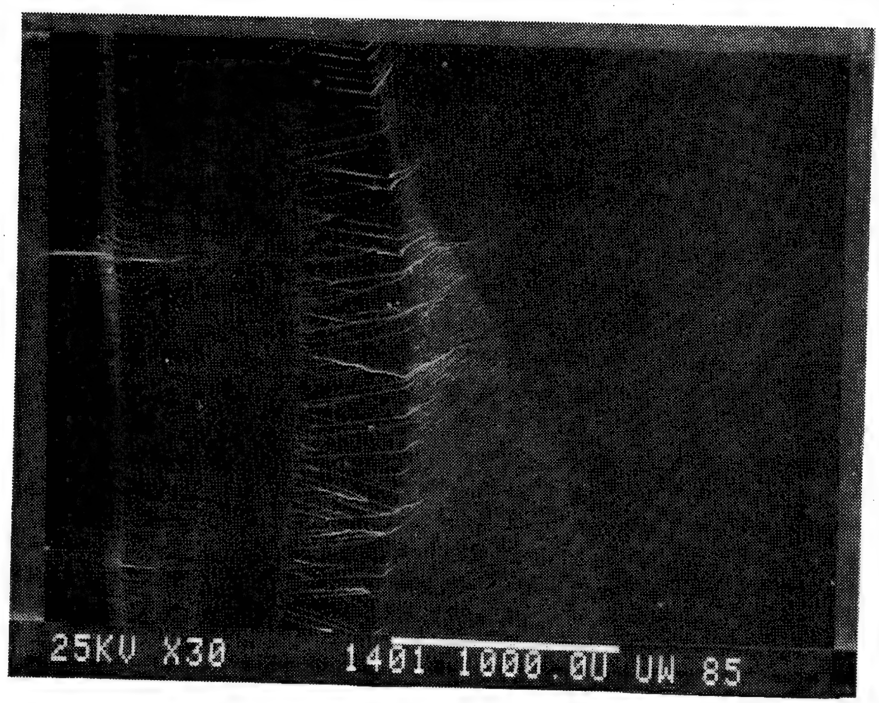

Figure 63. Photograph of ERX-4901B(MPDA) Fracture Specimen NFBAW4, 23°C, Moisture-Saturated.

Photograph shows ridges caused by arrest and propagation of crack front.

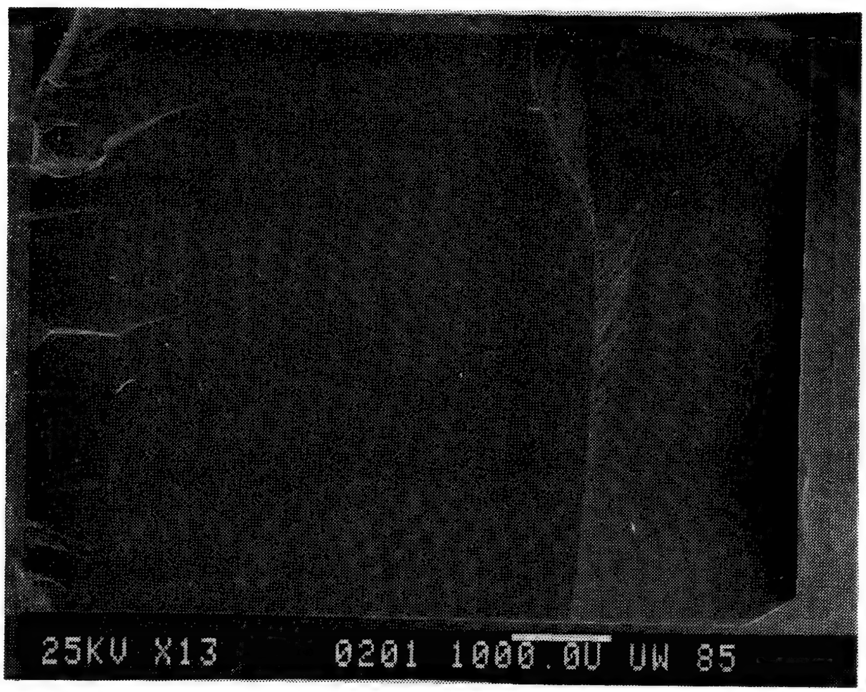

Figure 64. Overall View of ERX-4901B(MPDA) Fracture Specimen NFBBD8, 82°C, Dry Condition.

Cut notch is at the left of the photograph with what could be a ridge indicating a crack arrest in the right half of the photograph.

SECTION 7

CONCLUSIONS

Two new neat resin systems, viz., American Cyanamid CYCOM 1806 and Union Carbide ERX-4901B(MPDA), were successfully cast into various test specimens and mechanically characterized. Some additional characterization of a previously tested resin, viz, American Cyanamid CYCOM 907 (formerly BP907) was performed at -80°C, dry to enhance its data base. Tension, torsional shear, Iosipescu shear, single-edge notched-bend fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion tests were conducted to generate mechanical properties as functions of temperature and moisture. Properties generated for these neat resins were Young's modulus, E, Poisson's ratio, ν, shear modulus, G, tensile ultimate strength, σ^u, shear ultimate strength, τ^u, coefficient of thermal expansion, α, coefficient of moisture expansion, β, and Mode I strain energy release rate G_{IC}.

Four carbon fiber-reinforced unidirectional composites, viz., Hercules AS4/3502, NARMCO AS6/5245-C, American Cyanamid T300/CYCOM 907, and C6000/CYCOM 1806 were tested. Flat panels were supplied by NASA-Langley in sufficient quantities to perform various mechanical testing on these four composites. All specimens were machined and prepared in the CMRG fabrication laboratory.

Longitudinal and transverse tension, in-plane shear and transverse coefficient of thermal expansion, and transverse coefficient of moisture expansion tests were conducted to generate mechanical properties as a function of temperature. Properties generated for the four composite

materials were axial and transverse moduli, E_{11} and E_{22}, major Poisson's ratio, ν_{12}, in-plane shear modulus, G_{12}, tensile ultimate strengths, $\sigma_{11}{}^{u}$ and $\sigma_{22}{}^{u}$, shear ultimate strength, $\tau_{12}{}^{u}$, transverse coefficient of thermal expansion, α_{22}, and transverse coefficient of moisture expansion, β_{22}.

The neat resin mechanical properties will be input to a curve-fit computer program to reduce each property to an equation describing that property as a function of temperature and moisture. After the curve-fit equations are generated they will be incorporated into the Composite Materials Research Group's micromechanics computer program WYO2D and predictions of composite response of these high strength carbon fiber-reinforced composites will be made. Correlations of these predictions will be done to verify the finite element micromechanical model. These predictions and correlations will be presented in a subsequent report.

Processability of the two neat resin systems was quite different. The CYCOM 1806 epoxy was much more viscous and required more effort to cast than the ERX-4901B(MPDA). The CYCOM 1806 epoxy was premixed by the manufacturer while the ERX-4901B(MPDA) required formulation just prior to being cast into test specimens. The ERX-4901B(MPDA) epoxy exhibited the viscosity of water, similar to the ERX-4901A(MDA) version characterized last year [2]. It required the sealing of mold seams to prevent the watery resin from leaking out of the molds. The cure cycle for the ERX-4901B(MPDA) epoxy was quite long, being comparable to the MDA version tested last year [2].

The CYCOM 1806 epoxy performed as well as any neat resin tested to date [1,2]. It has only a slightly lower Young's modulus and shear modulus than other resin systems, with comparable tensile and shear

strengths at most environmental conditions. The CYCOM 1806 did degrade slightly more at the hot, wet conditions than some of the previous resin systems tested.

The ERX-4901B(MPDA) epoxy exhibited the highest room temperature, dry Young's modulus of any polymer tested to date, viz, 5.6 GPa (0.81 Msi). It also exhibited very high tensile and shear strengths and shear modulus, as high or higher than the MDA version of this epoxy [2]. However, The ERX-4901B(MPDA) degraded to a much greater degree at all moisture-saturated conditions than any previous resin system. Even the room temperature, wet properties were quite poor.

The CYCOM 1806 reached a moisture saturation level of only 2.9 percent while the ERX-4901B(MPDA) absorbed 10.2 percent moisture at saturation, which is the highest moisture level of all ten neat resins tested to date in this program.

The CYCOM 1806 epoxy was judged to be a good candidate for use in high performance composites. It processed relatively easily and performed almost as well as the HX-1504 and 5245-C matrix materials tested last year. The ERX-4901B(MPDA) epoxy is a model resin system similar to the ERX-4901A(MDA) epoxy tested last year. It has excellent tensile and shear properties at the room temperature, dry condition, but degraded rapidly at elevated temperatures and after being moisture saturated at all test temperatures. Although the ERX-4901B(MPDA) version of this epoxy had slightly higher stiffness and strength values then the ERX-4901A(MDA) version, it degraded much more readily and to a higher degree than the (MDA) version tested in last year's program.

The four carbon fiber-reinforced composites tested provided the first composite property data for use in micromechanics correlation

studies. The composite material test data indicated the materials retained their properties quite well at the 100°C test temperature. The T300/CYCOM 907 composite degraded to the greatest degree of the four composites as expected. Since each composite incorporated a different fiber, direct comparisons are difficult to make.

Additional scanning electron microscope photographs were taken to further document fracture surfaces in unreinforced (neat) polymers. A large library of SEM photographs has been accumulated during the three years of this grant, providing a basis for future study.

Lack of satisfaction of the isotropic relation relating the neat resin experimental stiffness parameters E, ν, and G was again noted. Temperature and moisture conditions appeared to exacerbate the differences between isotropic theory and the experimental values.

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4. "Standard Test Method for Tensile Properties of Oriented Fiber Composites", ASTM D3039, Section 15.03, American Society for Testing Materials, 1985.

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7. "Union Carbide Technical Bulletin No. 465-252", Union Carbide Corporation, Chicago, IL, October 1982.

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10. Walrath, D. E. and Adams, D. F., "Iosipescu Shear Properties of Graphite Fabric/Epoxy Composite Laminates", Report No. UWME-DR-501-103-1, Department of Mechanical Engineering, University of Wyoming, June 1985.

11. "CYCOM Structural Resins, Advanced Composites, and Prepregs," American Cyanamid Company, Wayne, New Jersey, April 1984.

APPENDIX A

Tables of Individual Test Specimen Results for the Three Neat Resins and Four Carbon Fiber-Reinforced Composites

Table A1

INDIVIDUAL CYCOM 1806 NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTAAD 1	23	---	---	2.13*	2.96	0.43	0.38
2		84.1	12.2	3.16	3.17	0.46	0.40
3		---	---	---	3.10	0.45	0.38
4		92.4	13.4	3.66	3.24	0.47	0.41
5		74.4*	10.8*	2.75	2.83	0.41	0.38
6		104.8*	15.2*	5.07*	2.34*	0.34*	0.36
Average		88.3	12.8	3.19	3.06	0.44	0.39
Standard Deviation		5.9	0.8	0.46	0.17	0.02	0.021

Table A2

INDIVIDUAL CYCOM 1806 NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTABD 1	82	77.5	11.2	4.83	2.58	0.38	0.47
2		77.4	11.2	5.32	2.56	0.37	0.46
3		77.6	11.3	4.94	2.49	0.36	0.47
4		70.5	10.2	3.42*	2.48	0.36	0.41
5		74.3	10.8	5.50*	2.31	0.33	0.48
Average		75.5	10.9	5.03	2.48	0.36	0.46
Standard Deviation		3.1	0.5	0.25	0.11	0.02	0.03

*Not included in average

Table A3

Individual CYCOM 1806 NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate (MPa)	Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	(Msi)	Poisson's Ratio
NTACD	0	121	62.7	9.1	5.03	2.48	0.36	0.52
	4		65.5	9.5	--	--	--	--
	5		60.7	8.8	4.32	2.41	0.35	0.45
	7		68.2	9.9	8.18*	2.21	0.32	0.44
	8		--	--	--	2.21	0.32	0.47
	10		60.0	8.7	3.87	2.34	0.34	0.44
	11		62.7	9.1	7.72*	2.55	0.37	0.42
	12		62.0	9.0	5.95*	2.41	0.35	0.44
	13		65.5	9.5	4.87	2.55	0.37	0.44
Average			63.4	9.2	4.81	2.38	0.35	0.45
Standard Deviation			2.8	0.4	0.79	0.14	0.02	0.03

*Not included in average

Table A4

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NSAAD	1	23	93.7	13.6	15.05	1.52*	0.22*
	2		69.6*	10.2*	6.71*	1.38	0.20
	3		95.8	13.9	18.60	1.10	0.16
	4		91.0	13.2	17.64	1.10	0.16
	5		89.6	13.0	13.64	1.38	0.20
Average			92.5	13.4	17.10	1.24	0.18
Standard Deviation			2.8	0.4	1.84	0.16	0.02

Table A5

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NSABD	1	82	68.9	10.0	16.00	1.10	0.16
	2		64.8	9.4	12.69*	0.69	0.14
	3		67.6	9.8	14.94	0.90	0.13
	4		68.2	9.9	12.95	0.90	0.13
	5		56.5	8.2	15.92	0.90	0.13
Average			65.2	9.5	14.95	0.95	0.14
Standard deviation			5.1	0.7	1.42	0.09	0.01

*Not included in average

Table A6

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NSACD	1	121	41.4	6.0	15.51	0.69	0.10
	2		46.2	6.7	15.30	0.97	0.14
	3		51.7	7.5	10.25*	0.97	0.14
	4		43.4	6.3	16.67	0.62*	0.09*
	5		48.3	7.0	15.41	0.83	0.12
Average			46.2	6.7	15.72	0.86	0.13
Standard Deviation			4.0	0.6	0.64	0.13	0.02

*Not included in average

Table A7

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stresss (MPa)	(ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	(Msi)	Poisson's Ratio
NTBAD	1	23	83.4	12.1	1.58	--	--	0.33
	2		104.8	15.2	2.04*	5.31	0.77	--
	3		100.7	14.6	--	5.60	0.81	0.32
	4		102.7	14.9	1.60	6.96*	1.01*	0.34
	5		106.9	15.5	1.95	5.93	0.86	0.33
	6		86.9	12.6	1.69	4.96*	0.72*	0.26*
	7		95.2	13.8	1.70	6.82*	0.99*	0.37*
Average			97.2	14.1	1.70	5.61	0.81	0.33
Standard Deviation			9.1	1.3	0.15	0.31	0.05	0.01

*Not included in average

Table A8

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate (MPa)	Stress (ksi)	Ultimate Strain (Percent)	Tensile (GPa)	Modulus (Msi)	Poisson's Ratio
NTBBD	1	82	68.2	9.9	2.45	3.58	0.52	0.47
	2		75.1	10.9	2.25	4.20	0.61	0.38
	3		73.1	10.6	2.67	3.93	0.57	0.42
	4		74.4	10.8	2.68	4.07	0.59	0.41
	5		73.6	10.7	2.83	3.72	0.54	0.43
	6		71.0	10.3	2.80	3.65	0.53	0.37
Average			72.6	10.5	2.61	3.86	0.56	0.41
Standard Deviation			2.6	0.4	0.22	0.25	0.04	0.04

*Not included in average

Table A9

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTBED	1	100	35.2*	5.1*	16.36	3.10*	0.24*	0.45
	2		35.2*	5.1*	---	2.14	0.31	0.41
	3		42.7	6.2	15.92	1.86*	0.27*	0.46
	4		43.4	6.3	---	2.00	0.29	0.42
	5		45.5	6.6	---	2.21	0.32	0.37
	6		40.0	5.8	13.21	3.10*	0.24*	0.40
	7		45.5	6.6	12.50*	2.41	0.35	0.42
Average			43.4	6.3	15.16	2.19	0.32	0.42
Standard Deviation			2.3	0.3	1.71	0.17	0.03	0.03

*Not included in average

Table A10

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTBCD	2	121	6.2	0.9	8.18	0.10	0.02	0.43
	4		2.8	0.4	--	0.06	0.01	0.46
Average			4.5	0.7	8.18	0.08	0.02	0.45
Standard Deviation			--	--	--	--	--	0.02

Table A11

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NSBAD	1	23	66.9*	9.7*	3.60*	3.58*	0.52*
	2		134.4	19.5	--	1.79*	0.26*
	3		129.6	18.8	5.79	2.21	0.32
	4		109.6	15.9	4.82	2.27	0.33
	5		133.8	19.4	12.24*	2.21	0.32
Average			126.9	18.4	5.31	2.23	0.32
Standard Deviation			11.7	1.7	0.69	0.03	0.00

*Not included in average

Table A12

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSBBD	1	82	93.1	13.5	8.33	2.28	0.33
	2		95.8	13.9	6.89	1.72*	0.25*
	3		95.8	13.9	12.22*	1.93	0.28
	5		52.4*	7.6*	2.37	2.07	0.30
	6		52.4*	7.6*	2.37	2.07	0.30
Average			95.0	13.8	5.00	2.09	0.30
Standard Deviation			1.6	0.2	3.08	0.14	0.02

Table A13

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TORSIONAL SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSBCD	2	121	24.8	3.6	13.21	0.48	0.07
	3		22.7	3.3	19.17*	0.28	0.04*
	4		24.8	3.6	10.69*	0.48	0.07
	5		22.7	3.3	15.37	0.41	0.06
	6		13.8*	2.0*	---	0.48	0.07
Average			23.8	3.5	14.29	0.46	0.07
Standard Deviation			1.2	0.2	1.53	0.04	0.01

*Not included in average

Table A14

INDIVIDUAL CYCOM 1806 NEAT RESIN TENSILE TESTS - MOISTURE-SATURATED CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPA)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTAAW 0	23	--	--	--	3.03	0.44	0.45
1		--	--	--	3.03	0.44	0.43
2		79.3	11.5	6.58	3.03	0.44	0.42
3		--	--	--	2.96	0.43	0.45
4		--	--	--	3.03	0.44	0.44
6		77.9	11.3	4.05	3.03	0.44	0.45
7		--	--	--	3.03	0.44	0.45
9		--	--	--	3.03	0.44	0.44
10		73.8	10.7	3.60	2.96	0.43	0.48
11		79.3	11.5	6.08	2.96	0.43	0.49
12		73.1	10.6	3.51*	2.96	0.43	0.50
13		80.0	11.6	6.86*	3.03	0.44	0.51
Average		77.2	11.2	5.08	3.02	0.44	0.46
Standard Deviation		3.0	0.4	1.47	0.02	0.00	0.03

*Not included in average

Table A15

INDIVIDUAL CYCOM 1806 NEAT RESIN TENSILE TESTS - MOISTURE-SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTABW	1	82	35.8	5.2	--	1.45	0.21	--
	2		31.7	4.6	--	1.52	0.22	0.56*
	3		33.8	4.9	13.78	1.65	0.24	0.63*
	4		36.5	5.3	9.43	1.86	0.27	0.50
	5		37.9	5.5	10.59	1.93*	0.28*	0.38
	6		37.2	5.4	8.30	1.86	0.27	0.45
Average			35.5	5.2	10.53	1.67	0.24	0.44
Standard Deviation			2.3	0.3	2.36	0.19	0.03	0.06

Table A16

INDIVIDUAL CYCOM 1806 NEAT RESIN TENSILE TESTS - MOISTURE-SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTACW	1	121	11.7	1.7	7.91	0.48*	0.07*	0.24
	2		11.7	1.7	13.74	0.34	0.05	0.62*
	3		12.4	1.8	14.48	0.34	0.05	0.41
	4		9.7	1.4	10.78*	0.28	0.04	0.51*
	5		9.0*	1.3*	12.09	0.28	0.04	0.48
Average			11.4	1.7	13.44	0.31	0.05	0.38
Standard Deviation			1.2	0.2	1.22	0.03	0.01	0.10

*Not included in average

Table A17

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSAAW	1	23	75.8	11.0	15.38	1.24*	0.18*
	2		71.7	10.4	15.49	1.03	0.15
	3		71.7	10.4	10.70*	1.17	0.17
	4		73.1	10.6	11.50	1.03	0.15
	5		72.3	10.5	18.37*	0.97	0.14
Average			72.9	10.6	14.12	1.05	0.15
Standard Deviation			1.7	0.2	2.27	0.08	0.01

Table A18

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSABW	1	82	45.5	6.6	15.40	0.69	0.10
	2		40.0	5.8	19.96	0.69	0.10
	3		46.2	6.7	17.53	0.62	0.09
	4		46.2	6.7	30.01	1.24*	0.18*
	5		45.5	6.6	46.91*	0.62	0.09
Average			44.7	6.5	20.72	0.66	0.10
Standard Deviation			2.6	0.4	6.46	0.04	0.01

*Not included in average

Table A19

INDIVIDUAL CYCOM 1806 NEAT RESIN TORSIONAL SHEAR TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSACW	1	121	22.1	3.2	14.39	0.21	0.03
	2		22.7	3.3	14.90	0.21	0.03
	3		24.8	3.6	9.81	0.28	0.04
	4		24.1	3.5	6.33*	0.41*	0.06*
	5		23.4	3.4	17.47*	0.21	0.03
Average			23.4	3.4	13.03	0.23	0.03
Standard Deviation			1.1	0.2	2.80	0.04	0.01

Table A20

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	(ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	(Msi)	Poisson's Ratio
NTBAW	6	23	9.0	1.3	1.25*	0.92*	0.13*	0.49
	7		9.0	1.3	1.48*	0.79	0.11	0.49
	8		5.5*	0.8*	0.71	0.74	0.11	0.50
	9		6.2*	0.9*	0.83	0.75	0.11	0.43
Average			9.0	1.3	0.77	0.76	0.11	0.48
Standard Deviation			0.0	0.0	0.08	0.22		0.03

*Not included in average

Table A21

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTBDW	1	60	1.4*	0.2*	2.44	0.07*	0.01*	0.43
	2		2.1	0.3	2.68	0.14	0.02	0.44
	3		2.1	0.3	2.02	0.14	0.02	0.36*
	4		2.1	0.3	4.17*	0.14	0.02	0.41
	5		1.4*	0.2*	2.76	0.07*	0.01*	0.52*
Average			2.1	0.3	2.48	0.14	0.02	0.43
Standard Deviation			0.0	0.0	0.33	0.00	0.00	0.02

Table A22

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TENSILE TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NTBCW	2	82	0.1	.01	2.80	--	--	0.30
	3		0.4	.06	1.20	0.07	0.01	0.36
Average			0.2	.04	2.00	--	--	0.33

*Not included in average

Table A23

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TORSIONAL SHEAR TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSBAW	1	23	40.0	5.8	2.44	1.52	0.22
	2		26.9*	3.9*	3.19	0.83	0.12
	3		37.2	5.4	19.18*	0.76*	0.11*
	4		72.4*	10.5*	19.06*	2.00*	0.29*
	5		60.7	8.8	4.19	1.45	0.21
Average			46.0	6.7	3.27	1.27	0.18
Standard Deviation			12.8	4.9	0.88	0.38	0.06

Table A24

INDIVIDUAL ERX-4901B(MPDA) NEAT RESIN TORSIONAL SHEAR TESTS - MOISTURE SATURATED CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NSBBW	1	82	1.4	0.2	50.36*	0.00*	0.00*
	2		15.9*	2.3*	10.80	0.14*	0.02*
	3		3.4	0.5	48.19*	0.00*	0.00*
	4		2.1	0.3	20.15	0.07	0.01
	5		1.4	0.2	13.35	0.04	0.01
Average			2.1	0.3	14.77	0.06	0.01
Standard Deviation			0.9	0.1	4.83	0.02	0.00

*Not included in average

Table A25

INDIVIDUAL TENSION STRENGTHS AND MODULI FOR
CYCOM 907 NEAT RESIN, DRY

Specimen		Test Temperature (°C)	Tensile Strength (MPa)	(ksi)	Tensile Moduli (GPa)	(Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio
NCTPO	1	-80°	103	14.9	3.7	0.53	3.4	0.05*
	2		81	11.8	3.9	0.56	2.2	--
	3		101	14.6	3.9	0.57	2.9	0.06*
	4		90	13.1	4.2	0.61	2.1	0.17
	5		106	15.3	4.5	0.71	2.7	0.17
	6		113	16.4	4.5	0.65	2.5	0.13
	7		107	15.5	4.1	0.60	3.0	0.13
Average			101	14.7	4.1	0.59	2.8	0.15
Standard Deviation			7	0.9	0.3	0.04	0.2	0.02
LTDPO	7 [2]	23°	82	11.9	3.2	0.47	3.1	0.42
	8		96	13.9	3.2	0.47	5.1	0.42
	9		81	11.7	3.3	0.48	3.0	0.41
Average			86	12.5	3.3	0.47	3.7	0.42
Standard Deviation			8	1.2	0.0	0.06	1.2	0.00
LTDP	11 [2]	82°	68	9.9	2.8	0.41	5.0	0.44
	12		66	9.5	2.7	0.39	6.9	0.41
	13		67	9.7	2.8	0.41	5.4	0.43
	14		66	9.6	2.7	0.39	5.7	0.41
	15		61*	8.8*	2.8	0.40	2.9	2.43
Average			67	9.7	2.8	0.40	5.4	0.42
Standard Deviation			1	0.2	0.1	0.01	0.0	0.01
LTDP	21 [2]	121°	11	1.6	0.6	0.08	>8.2	0.31
	22		10	1.5	0.3*	0.04*	>8.2	0.44
	23		15	2.1	1.0	0.15	>8.2	0.35
	24		16	2.3	1.0	0.14	>8.2	0.39
	25		14	2.0	0.8	0.11	>8.2	0.39
Average			14	2.0	0.8	0.12	>8.2#	0.38
Standard Deviation			2	0.3	0.2	0.03		0.02

*Not included in average

Table A26

INDIVIDUAL IOSIPESCU SHEAR STRENGTHS AND MODULI FOR CYCOM 907 NEAT RESIN, DRY

Specimen		Test Temperature (°C)	Shear Strength (MPa)	(ksi)	Shear Modulus (GPa)	(Msi)	Ultimate Shear Strain (percent)
NCBPO	1	-80°	47.6	6.9	1.6	0.24	3.02
	2		55.1	8.0	1.8	0.26	3.44
	3		52.4	7.6	1.7	0.25	3.19
	4		55.1	8.0	2.1	0.31	3.44
	5		63.4	9.2	2.3*	0.33*	1.84*
	6		55.1	8.0	1.8	0.26	3.28
Average			55.1	8.0	1.8	0.26	3.27
Standard Deviation			4.8	0.7	0.2	0.03	0.18
LIDPO	1 [2]	23°	27.6	4.0*	1.24	0.18	2.30
	2		33.8	4.9	1.31	0.19	3.00
	3		53.1	7.7	1.17	0.17	4.90
	4		34.5	5.0	1.17	0.17	3.00
	5		58.6	8.5	1.03	0.15	>6.0
Average			44.8	6.5	1.17	0.17	3.30
Standard Deviation			12.4	1.8	0.07	0.01	1.10
LIDP	14	82°	46.9	6.8	1.17	0.17	>6.0
	15		46.9	6.8	1.03	0.15	>6.0
	16		46.2	6.7	0.97	0.14	>6.0
	17		44.8	6.5	0.97	0.14	>6.0
	18		43.4	6.3	0.97	0.14	>6.0
Average			45.5	6.6	1.03	0.15	>6.0#
Standard Deviation			1.4	0.2	0.07	0.01	
LIDP	21	121°	24.1	3.5	0.69	0.10	>6.0
	22		28.3	4.1	0.83	0.12	>6.0
	23		27.6	4.0	0.76	0.11	>6.0
	24		29.0	4.2	0.76	0.11	>6.0
	25		29.0	4.2	0.83	0.12	>6.0
Average			27.6	4.0	0.76	0.11	>6.0#
Standard Deviation			2.1	0.3	0.07	0.01	

*Not included in average

#Strain Gage saturated, ultimate strain not measured

Table A27

INDIVIDUAL FRACTURE TOUGHNESS VALUES FOR
1806 NEAT EPOXY AT DRY CONDITION

Specimen Number		Test Temperature (°C)	Mode I Strain Energy Release Rate (J/m^2)	$(\frac{in\text{-}lb}{in})$
NFDEO	1	23°	141	0.8
	2		51*	0.3*
	3		136	0.8
	4		104	0.6
	5		109	0.6
	6		104	0.6
	7		102	0.6
	8		163*	0.9*
	9		156*	0.9*
	10		114	0.7
		Average	116	0.7
		Standard Deviation	16	0.1
NFAEO	1	82°	401	2.3
	2		406	2.3
	3		360	2.1
	4		119*	0.7*
	5		166*	0.9*
	6		166*	0.9*
	7		14*	0.1*
	8		397	2.3
	9		581*	3.3*
	10		309	1.8
		Average	375	2.1
		Standard Deviation	41	0.2
NFCEO	1	121°	812*	4.6*
	3		732*	4.2*
	4		808*	4.6*
	7		55	0.3
	8		93	0.5
	9		199	1.1
	10		71	0.4
		Average	105	0.6
		Standard Deviation	65	0.4

*Not included in average

Table A28

INDIVIDUAL FRACTURE TOUGHNESS VALUES FOR 1806 NEAT EPOXY AT MOISTURE SATURATED CONDITION

Specimen Number		Test Temperature (°C)	Mode I Strain Energy Release Rate (J/m^2)	($\frac{in\text{-}lb}{in}$)
NFWEO	1	23°	407*	2.3*
	2		326	1.9
	3		451*	2.6*
	4		295	1.7
	5		303	1.7
	6		231*	1.3*
	7		213*	1.2*
	8		253	1.4
	10		319	1.8
	12		280	1.6
		Average	296	1.7
		Standard Deviation	27	0.2
NFBEO	2	82°	178	1.0
	3		228*	1.3*
	4		28*	0.2*
	5		90	0.5
	6		177	1.0
	7		173	1.0
	8		221*	1.3*
	9		120	0.7
	10		29*	0.2*
		Average	148	0.8
		Standard Deviation	40	0.2
NFEEO	1	121°	66	0.4
	2		269*	1.5*
	3		132	0.8
	4		25*	0.1*
	5		87	0.5
	6		113	0.6
	7		76	0.4
	8		123	0.7
	9		180	1.0
	10		19*	0.1*
		Average	111	0.6
		Standard Deviation	39	0.2

*Not included in average

Table A29

INDIVIDUAL FRACTURE TOUGHNESS VALUES FOR
ERX-4901B(MPDA) NEAT EPOXY AT DRY CONDITION

Specimen Number		Test Temperature (°C)	Mode I Strain Energy Release Rate (J/m^2)	($\frac{in\text{-}lb}{in}$)
NFDBO	1	23°	272	1.6
	2		314*	1.8*
	3		355*	2.0*
	4		79*	0.5*
	5		156	0.9
	6		114	0.7
	7		119	0.7
	8		304	1.7
	9		211	1.2
	10		161	0.9
		Average	191	1.1
		Standard Deviation	74	0.4
NFABO	1	82°	80	0.5
	2		78	0.4
	3		80	0.5
	4		108*	0.6*
	5		56*	0.3*
	6		84	0.5
	7		98	0.6
	8		116*	0.7*
	9		56*	0.3*
	10		80	0.5
		Average	83	0.5
		Standard Deviation	7	0.0

None Tested at 121°

*Not included in average

Table A30

INDIVIDUAL FRACTURE TOUGHNESS VALUES FOR
ERX-4901B(MPDA) NEAT EPOXY AT MOISTURE SATURATED CONDITION

Specimen Number		Test Temperature (°C)	Mode I Strain Energy Release Rate (J/m^2)	($\frac{in\text{-}lb}{in}$)
NFWBO	1	23°	48	0.3
	2		84*	0.5*
	3		37	0.2
	4		56	0.3
	5		46	0.3
	6		49	0.3
	7		64	0.4
	8		115*	0.7*
	9		24*	0.1*
	10		19	0.1
		Average	50	0.3
		Standard Deviation	9	0.1
NFBBO	1	82°	48*	0.27*
	2		72*	0.41*
	3		5	0.03
	4		1*	0.01*
	5		2	0.01
	6		5	0.03
	7		3	0.02
	8		6	0.03
	9		1*	0.01*
		Average	4	0.02
		Standard Deviation	2	0.01

None Tested at 121°

*Not included in average

Table A31

INDIVIDUAL FRACTURE TOUGHNESS VALUES FOR
CYCOM 907 NEAT EPOXY AT DRY CONDITION

Specimen Number		Test Temperature (°C)	Mode I Strain Energy Released Rate (J/m^2)	($\frac{in\text{-}lb}{in}$)
NCBFO	1	-80°	123*	0.7*
	2		171	1.0
	3		149	0.9
	4		46*	0.3*
	5		468	2.7
	6		491	2.8
	7		406	2.3
	8		554*	3.2*
	9		579*	3.3*
	10		326	1.9
	11		188	1.1
	12		204	1.2
	13		569*	3.2*
	14		563*	3.2*
	15		230	1.3
		Average	293	1.7
		Standard Deviation	133	0.8

*Not included in average

Table A32

INDIVIDUAL COEFFICIENT OF THERMAL EXPANSION RESULTS FOR TWO NEAT RESIN SYSTEMS

Coefficient of Thermal Expansion (CTE) ($10^{-6}/°C$)

Resin System	Specimen Number	Dry	Moisture-Saturated Specimen Number	
CYCOM 1806	DN1801	58.4	D186W4	63.7 *
	DN1802	58.0	D186WB	62.8
	DN1803	48.1	D186WD	63.1
Average		58.2		63.2
Standard Deviation		0.2		0.5

Resin System	Specimen		-60°C	23°C	93°C**
ERX-4901B(MPDA)	DN4901	Dry	22.5	59.1	90.0
	DN4902		23.1	61.4	93.7
	DN4903		22.3	64.2	99.4
Average			22.6	61.6	94.4
Standard Deviation			0.4	2.6	4.7
			-60°C	23°C	93°C#
	D49BWA	Moisture	11.0	87.7	152.5
	D49BWB	Saturated	18.8	93.5	156.6
	D49BWC		10.8	90.3	157.3
Average			13.5	90.5	155.4
Standard Deviation			4.6	2.9	2.6

ERX-4901B(MPDA) Equations

(1) Dry CTE = 4.895E - 05/°C + 4.413E - 07 x T(°C)/°C
(2) 5.082E - 05/°C + 4.615E - 07 x T(°C)/°C
(3) 5.256E - 05/°C + 5.040E - 07 x T(°C)/°C
(4) Wet CTE = 6.647E - 05/°C + 9.252E - 07 x T(°C)/°C
(5) 7.277E = 05/°C + 8.998E - 07 x T(°C)/°C
(6) 6.828E - 05/°C + 9.577E - 07 x T(°C)/°C

* CYCOM 1806 CTE linear over temperature range
** CTE values calculated from equations 1 - 3
\# CTE values calculated from equations 4 - 6

Table A33

INDIVIDUAL COEFFICIENTS OF MOISTURE EXPANSION
OF THE TWO NEAT RESIN SYSTEMS TESTED

Resin System	Specimen Number	Coefficient of Moisture Expansion (10^{-3}/%M)
CYCOM 1806	DNMEC1	2.34
	DNMEC2	2.58
	DNMEC3	2.57
	DNMEC4	2.60
	DNMEC5	2.57
	DNMEC6	1.72
	Average	2.53
	Standard Deviation	
ERX-4901B(MPDA	D4901B0	1.01
	D4901B1	1.21
	D4901B2	0.74
	DN49011	0.67*
	DN49012	0.50*
	Average	1.00
	Standard Deviation	0.23

*Not included in average

Table A34

INDIVIDUAL AS4/3502 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATAA	1	23	1998.9	290.0	1.25	129.59	18.80	0.38
	2		1812.8	263.0	1.12	134.07	19.45	0.31
	3		2122.3*	307.9*	0.52*	132.76	19.26	0.42*
	4		1656.4	240.3	1.07	125.66	18.23	0.36
Average			1841.4	264.4	1.15	130.52	18.94	0.35
Standard Deviation			144.9	24.9	0.09	3.75	0.54	0.04

Table A35

INDIVIDUAL AS4/3502 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATCA	1	100	2098.9	304.5	--	173.70*	25.20*	--
	2		2189.9	317.7	--	--	--	--
	4		2163.0	313.8	1.43	132.34	19.20	0.30
	5		--	--	--	135.24	19.62	0.36
	6		1829.4	265.4	1.29	141.30	20.50	0.34
	7		1734.2*	251.6*	1.28	128.21	18.60	0.35
Average			2070.3	300.4	1.33	134.27	19.48	0.34
Standard Deviation			165.1	23.9	0.08	5.50	0.80	0.03

*Not included in average

Table A36

INDIVIDUAL AS6/5245-C AXIAL TENSION TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATAC 1	23	2448.4	355.1	1.57	133.24	19.33	0.31
2		2680.8	388.8	1.60	134.41	19.50	0.39
3		2522.2	365.8	1.65	128.20	18.60	0.33
Average		2550.5	369.9	1.61	131.95	19.14	0.34
Standard Deviation		118.8	17.2	0.04	3.30	0.48	0.04

Table A37

INDIVIDUAL AS6/5245-C AXIAL TENSION TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATCC 1	100	2495.9	362.1	1.59	156.05	22.64	0.24*
2		2433.9	353.1	1.61	148.89	21.60	0.32
3		2489.0	361.1	1.63	150.26	21.80	0.33
Average		2472.9	358.8	1.61	151.73	22.01	0.32
Standard Deviation		34.0	4.9	0.02	3.80	0.55	0.01

*Not included in average

Table A38

INDIVIDUAL T300/BP907 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATAB	1	23	1229.7*	178.4*	0.95	130.28	18.90	0.34
	2		1424.3	206.7	1.03	121.04	17.56	0.33
	3		1468.9	213.1	1.07	122.83	17.82	0.39
	4		1394.4	202.3	1.02	124.69	18.09	0.31
Average			1429.4	207.4	1.02	124.80	18.09	0.34
Standard Deviation			37.5	5.4	0.05	3.89	0.58	0.03

Table A39

INDIVIDUAL T300/BP907 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATCB	1	100	1270.8	184.3	1.23	102.70	14.90	0.54
	2		1334.2	193.5	1.17	115.80	16.80	0.44
	3		1226.6	177.9	1.01	121.31	17.60	0.34
Average			1277.2	185.2	1.14	113.27	16.40	0.44
Standard Deviation			54.1	7.8	0.11	9.56	1.40	0.10

*Not included in average

Table A40

INDIVIDUAL C6000/1806 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATAD	1	23	2001.7	290.4	1.39	141.17*	20.48*	0.36
	2		2233.3	324.2	1.56	134.55	19.52	0.40
	3		2061.0	299.0	1.38	132.62	19.24	0.37
	4		2138.2	310.2	1.38	129.59	18.80	0.35
Average			2108.6	306.0	1.43	132.25	19.20	0.37
Standard Deviation			100.2	14.6	0.09	2.50	0.40	0.02

Table A41

INDIVIDUAL C6000/1806 AXIAL TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NATCO	1	100	1825.1	264.7	1.30	131.65	19.10	0.44
	2		2151.9	312.1	1.52	142.68	20.70	0.27*
	3		209[illegible].2	304.3	1.47	141.30f	20.50	0.36
Average			2025.1	293.7	1.43	138.54	20.10	0.40
Standard Deviation			175.2	25.4	0.12	6.01	0.90	0.06

*Not included in average

Table A42

INDIVIDUAL AS4/3502 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTAA	1	23	61.3	8.9	0.71	8.96	1.30
	2		63.4	9.2	0.68	9.58	1.39
	3		66.9	9.7	0.73	9.44	1.37
Average			63.9	9.3	0.71	9.33	1.35
Standard Deviation			2.8	0.4	0.03	0.33	0.05

Table A43

INDIVIDUAL AS4/3502 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTCA	1	100	53.8	7.8	0.66*	8.13	1.18
	2		51.7	7.5	0.62	8.55	1.24
	4		43.4	6.3	0.50*	8.69	1.26
	5		48.9	7.1	0.55	8.69	1.26
Average			49.5	7.2	0.59	8.51	1.24
Standard Deviation			4.5	0.7	0.05	0.27	0.04

*Not included in average

Table A44

INDIVIDUAL AS4/3502 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTBA	1	121	48.9	7.1	0.61	8.34	1.21
	2		42.0	6.1	0.87*	8.55	1.24
	3		40.7	5.9	--	8.55	1.24
	4		44.1	6.4	0.50	9.10	1.32
Average			43.9	6.4	0.56	8.64	1.25
Standard Deviation			3.6	0.5	0.08	0.33	0.05

Table A45

INDIVIDUAL AS6/5245-C TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTAC	1	23	55.1	8.0	0.61	9.17	1.33
	2		55.8	8.1	0.60	9.51	1.38
	3		55.1	8.0	0.63	8.96	1.30
Average			55.3	8.0	0.61	9.21	1.33
Standard Deviation			0.4	0.1	0.02	0.28	0.04

*Not included in average

Table A46

INDIVIDUAL AS6/5245-C TRANSVERSE TENSION TEST - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTCC 1	100	48.3	7.0	0.61	8.34	1.21
2		45.5	6.6	0.60	8.07	1.17
3		46.2	6.7	0.58	7.93	1.15
Average		46.7	6.8	0.60	8.11	1.18
Standard Deviation		1.5	0.2	0.02	0.21	0.03

Table A47

INDIVIDUAL AS6/5245-C TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTBC 1	121	59.3	8.6	0.89	7.93	1.15
2		60.0	8.7	1.02*	6.69*	0.97*
3		57.2	8.3	0.79	8.48	1.23
Average		58.8	8.5	0.84	8.2	1.19
Standard Deviation		1.5	0.2	0.07	0.4	0.06

*Not included in average

Table A48

INDIVIDUAL T300/BP907 TRANSVERSE TENSILE TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTAB	1	23	87.5	12.7	1.10	7.93	1.15
	2		89.6	13.0	1.16	7.72	1.12
	3		84.8	12.3	1.14	7.44	1.08
Average			87.3	12.7	1.13	7.70	1.12
Standard Deviation			2.4	0.4	0.03	0.25	0.04

Table A49

INDIVIDUAL T300/BP907 TRANSVERSE TENSION TEST - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTCB	1	100	19.3	2.8	1.44	3.24	0.47
	2		17.9	2.6	0.86*	4.83*	0.70*
	3		18.6	2.7	1.72	3.45	0.50
Average			18.6	2.7	1.58	3.35	0.49
Standard Deviation			0.7	0.1	0.20	0.15	0.02

*Not included in average

Table A50

INDIVIDUAL T300/BP907 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NNTBB	1	121	6.0	0.87	3.33	0.21	0.03
	2		5.2	0.76	2.74	0.21	0.03
	3		5.6	0.81	3.18	0.21	0.03
Average			5.6	0.81	3.08	0.21	0.03
Standard Deviation			0.4	0.06	0.31	0.00	0.00

Table A51

INDIVIDUAL C6000/1806 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTAD	1	23	60.7	8.8	0.69	9.10	1.32
	2		66.9	9.7	0.79	8.82	1.28
	3		63.4	9.2	0.77	8.55	1.24
	4		64.1	9.3	0.79	8.48	1.23
Average			63.8	9.3	0.76	8.74	1.27
Standard Deviation			2.6	0.4	0.05	0.28	0.04

*Not included in average

Table A52

INDIVIDUAL C6000/1806 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTLD	1	100	72.4	10.5	1.07	7.93	1.15
	2		70.3	10.2	0.98	8.07	1.17
	3		70.3	10.2	0.95	8.34	1.21
Average			71.0	10.3	1.00	8.11	1.18
Standard Deviation			1.2	0.2	0.06	0.21	0.03

Table A53

INDIVIDUAL C6000/1806 TRANSVERSE TENSION TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
NTTBD	1	121	51.7	7.5	0.84	7.10	1.03
	2		53.1	7.7	0.81	7.65	1.11
	3		57.2	8.3	0.87	8.27	1.20
	4		42.0*	6.1*	0.59*	7.51	1.09
Average			54.0	7.8	0.84	7.63	1.11
Standard Deviation			2.9	0.4	0.03	0.48	0.07

*Not included in average

Table A54

INDIVIDUAL AS4/3502 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NISAA	1	23	112.4	16.3	4.80	6.20	0.90
	2		113.1	16.4	5.29	5.79	0.84
	3		101.4	14.7	3.16*	5.86	0.85
Average			109.0	15.8	5.05	5.95	0.86
Standard Deviation			6.6	1.0	0.35	0.22	0.03

Table A55

INDIVIDUAL AS4/3502 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NISCA	1	100	84.1	12.2	>6.00	6.09	0.88
	2		82.7	12.0	>6.00	6.12	0.89
	3		81.3	11.8	>6.00	6.11	0.89
Average			82.7	12.0	>6.00	6.11	0.89
Standard Deviation			1.4	0.2	0.84	0.01	0.00

*Not included in average

Table A56

INDIVIDUAL AS6/5245-C IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NISAC 1	23	122.7	17.8	> 6.0	5.93	0.86
2		118.6	17.2	Strain gage failed early	6.27	0.91
3		128.2	18.6	> 6.0 #	5.65	0.82
Average		123.2	17.9	> 6.0	5.95	0.86
Standard Deviation		4.8	0.7	--	0.31	0.05

Table A57

INDIVIDUAL AS6/5245-C IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NISCC 1	100	89.6	13.0	> 6.0 #	5.24	0.76
2		101.3	14.7	> 6.0 #	4.62	0.67
3		107.5	14.1	> 6.0 #	5.10	0.74
Average		99.5	13.9	> 6.0 #	4.99	0.72
Standard Deviation		9.1	0.9	--	0.33	0.05

#Strain gage saturated

*Not included in average

Table A58

INDIVIDUAL T300/BP907 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NISAB	1	23	100.6	14.6	> 6.0 #	4.96	0.72
	2		126.8	18.4	> 6.0 #	5.58	0.81
	3		108.2	15.7	> 6.0 #	5.38	0.78
Average			111.7	16.2	> 6.0 #	5.31	0.77
Standard Deviation			11.6	2.0	--	3.17	0.46

Table A59

INDIVIDUAL T300/BP907 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NISCB	1	100	62.7	9.1	> 6.0 #	1.52	0.22
	2		52.4	7.6	> 6.0 #	1.72	0.25
	3		47.6	6.9	> 6.0 #	1.38	0.20
Average			54.2	7.9	> 6.0 #	1.54	0.22
Standard Deviation			7.7	1.1		0.17	0.03

#Strain gage saturated

*Not included in average

Table A60

INDIVIDUAL C6000/1806 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NISAD	1	23	111.7	16.2	>5.84 #	4.89	0.71
	2		106.8	15.5	>5.82 #	4.89	0.71
	3		104.1	15.1	>6.00	5.17	0.75
Average			107.5	15.6	>5.83	4.98	0.72
Standard Deviation			3.9	0.6	0.01	0.16	0.02

Table A61

INDIVIDUAL C6000/1806 IOSIPESCU SHEAR TESTS - DRY CONDITION

Specimen No.		Test Temperature (°C)	Ultimate Shear Stress (MPa)	(ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	(Msi)
NISCD	1	100	74.5	10.8	> 6.0 #	4.55	0.66
	2		78.6	11.4	> 6.0 #	5.24	0.76
	3		81.4	10.7	> 6.0 #	4.00	0.58
Average			78.2	11.0	> 6.0	4.60	0.67
Standard Deviation			3.5	0.3		0.62	0.09

#Strain gage saturated

*Not included in average

Table A62

INDIVIDUAL TRANSVERSE COEFFICIENT OF THERMAL EXPANSION TEST RESULTS FOR FOUR CARBON-FIBER REINFORCED COMPOSITES AT DRY CONDITION

Material System	Specimen Number	Transverse Coefficient of Thermal Expansion CTE = C1 + C2(T) $C_1 (10^{-6}/°C)$	$C_2 (10^{-6}/°C^2)$
AS4/3502	D35901	30.9	---
	D35902	30.8	---
	D35903	30.8	---
	Average	30.8	
	Standard Deviation	0.1	
AS6/5245-C	D52901	33.4	---
	D52902	32.2	---
	D52903	32.8	---
	Average	32.8	
	Standard Deviation	0.6	
T300/BP907*	DBP9A1	30.0	0.195
	DBP9A2	30.3	0.198
	DBP9A3	30.8	0.185
	Average	30.4	0.196
	Standard Deviation	0.4	0.007
C6000/1806	D18901	33.1	---
	D18902	33.3	---
	D18903	33.3	---
	Average	33.2	
	Standard Deviation	0.1	

* CTE Non-linear over temperature range

Table A63

INDIVIDUAL TRANSVERSE COEFFICIENT OF MOISTURE EXPANSION TEST RESULTS FOR FOUR CARBON-FIBER REINFORCED COMPOSITES

Material System	Specimen Number	Transverse Coefficient of Moisture Expansion (10^{-3}/%M)
AS4/3502	DN35C1	5.14
	DN35C2	5.32
	DN35C4	3.54
	DN35C5	2.16*
	Average	4.67
	Standard Deviation	0.98
AS6/5245-C	DN52C1	8.11*
	DN52C2	3.22
	DN52C3	3.14
	DN52C4	4.61
	DN52C5	3.35
	DN52C6	5.76
	Average	4.02
	Standard Deviation	1.14
T300/BP907	DN90C1	2.79
	DN90C2	3.02
	DN90C3	2.09
	DN90C4	2.38
	Average	2.59
	Standard Deviation	0.29
C6000/1806	DN18C1	3.39*
	DN18C2	1.85*
	DN18C3	2.74
	DN18C4	2.83
	DN18C5	3.27
	DN18C6	2.47
	Average	2.83
	Standard Deviation	0.33

*Not included in average

Table A64

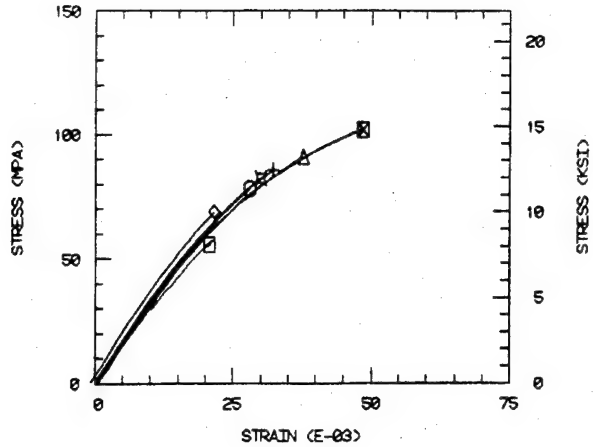
INDIVIDUAL FIBER VOLUME AND VOID VOLUME DETERMINATIONS FOR FOUR CARBON FIBER-REINFORCED COMPOSITES

Material System	Sample Number	Carbon Fiber Volume (percent)	Void Volume (percent)
AS4/3502	1	62.2	0.0
	2	68.3	2.5
	3	62.9	0.8
	Mean	64.5	1.1
	Standard Deviation	3.3	1.3
AS6/5245-C	1	63.3	1.3
	2	62.8	0.9
	3	63.2	1.1
	Mean	63.1	1.1
	Standard Deviation	0.3	0.3
T300/BP907	1	56.6	1.4
	2	59.2	1.9
	3	58.7	1.5
	Mean	58.2	1.6
	Standard Deviation	1.4	0.3
C6000/1806	1	63.1	1.6
	2	63.8	2.5
	3	63.4	1.4
	Mean	63.4	1.8
	Standard Deviation	0.4	0.6

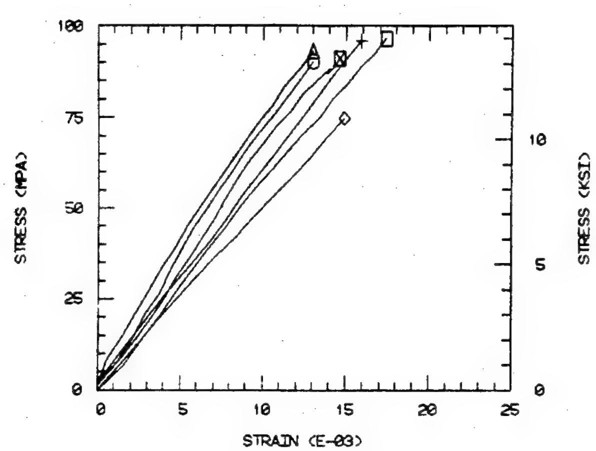
APPENDIX B

Individual Test Specimen Stress-Strain Curves for the Three Neat Resins and Four Carbon Fiber-Reinforced Composites

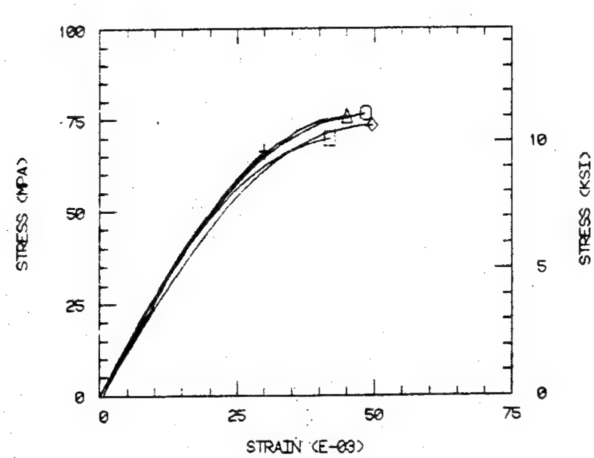
1806 NEAT, TENSION, 23 C, DRY



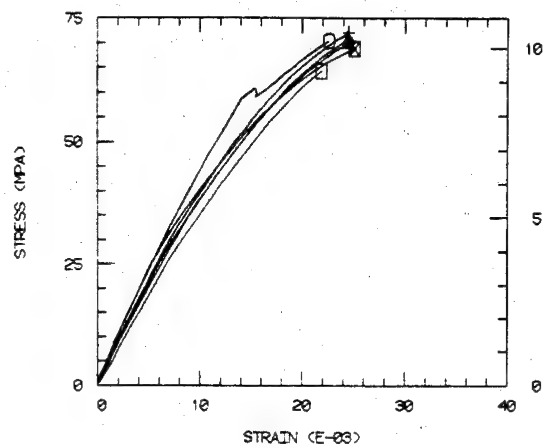
4901-B NEAT, TENSION, 23 C, DRY



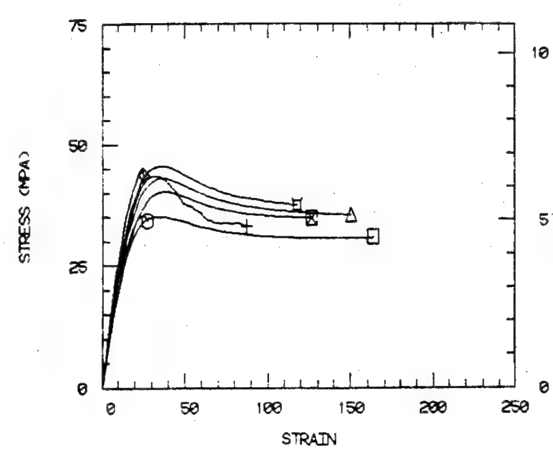
1806 NEAT, AXIAL TEN, 82 C, DRY



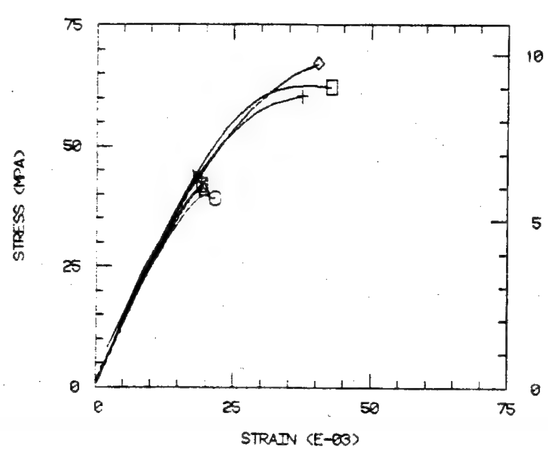
4901 MPDA, AXIAL TEN, 80 C, DRY



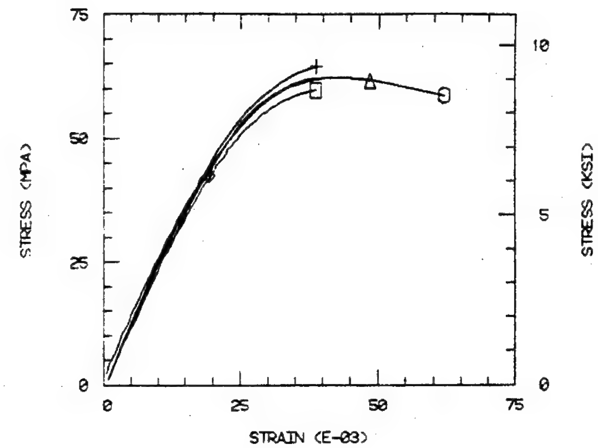
4901 MPDA, AXIAL TEN, 100 C, DRY



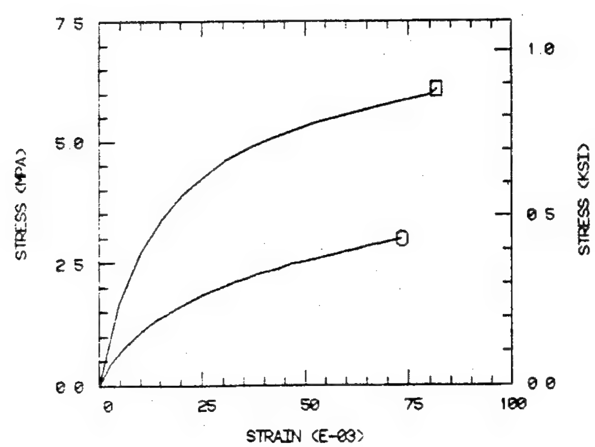
1806 NEAT, AXIAL TEN, 121 C, DRY



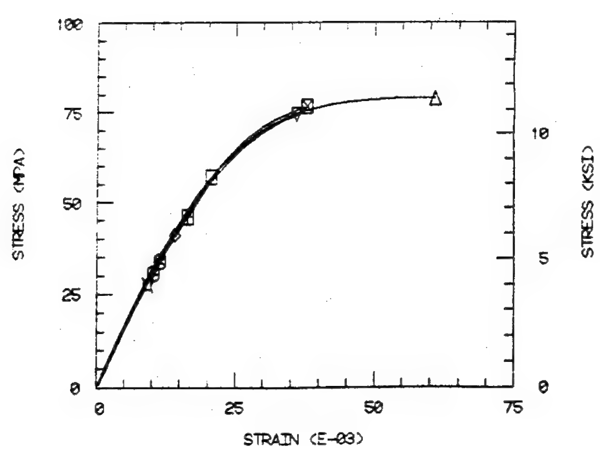
1806 NEAT, AXIAL TEN, 121 C, DRY



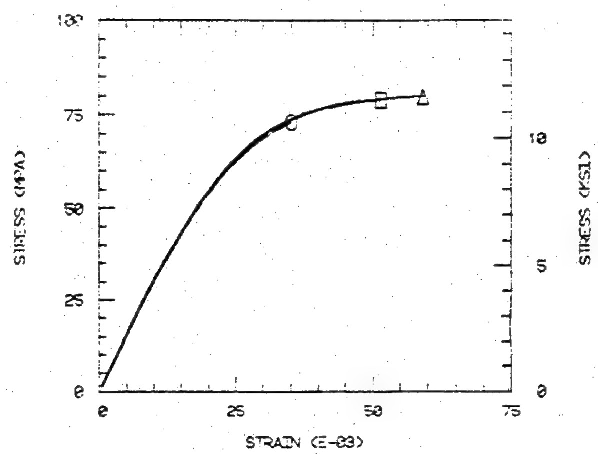
4901-B NEAT, AXIAL TEN, 121 C, DRY



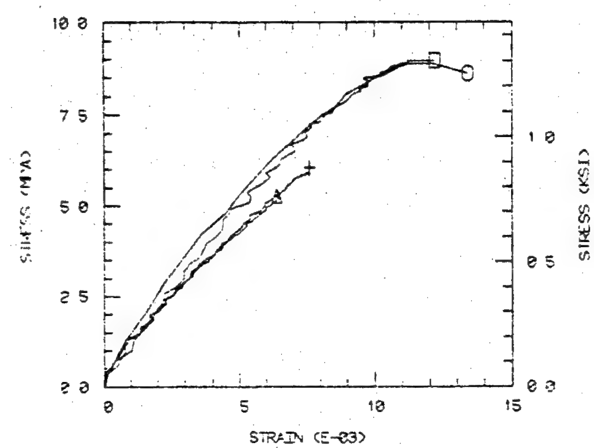
1806 NEAT, TENSION, 23 C, WET



1806 NEAT, TENSION, 23 C, WET



4901-3 NEAT, TENSION, 23 C, WET



SPACE

INTENTIONALLY

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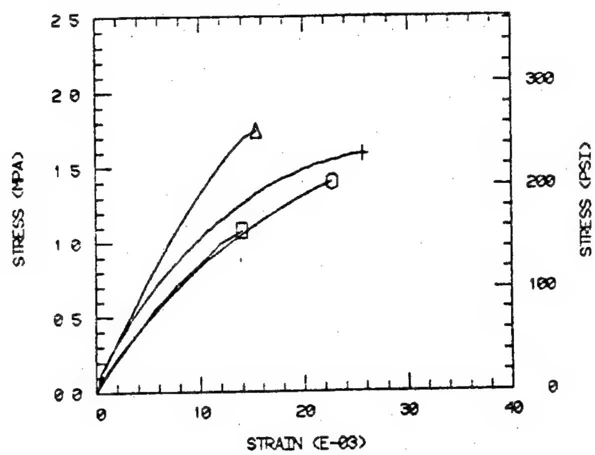
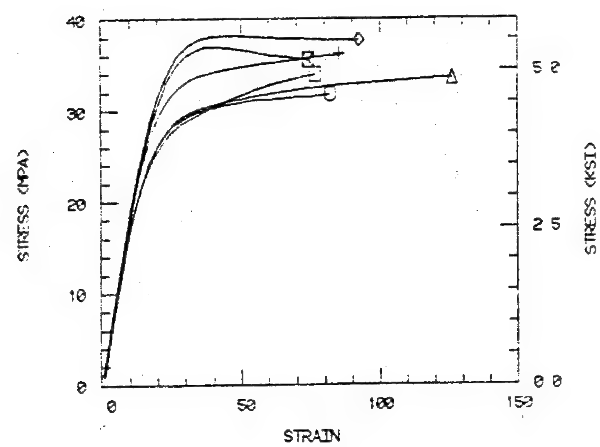
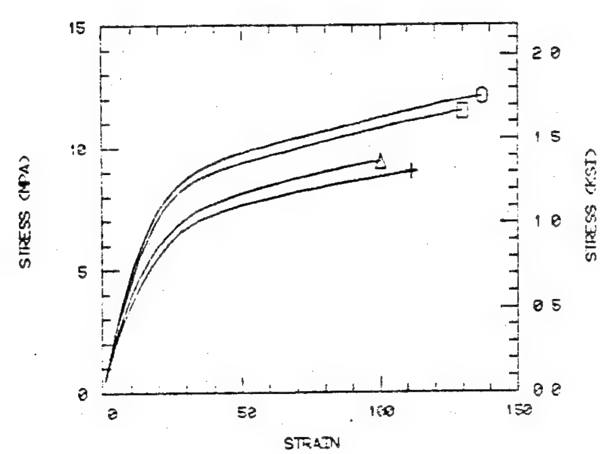
4901 MPDA NEAT, AXIAL TEN, 60 C, WET



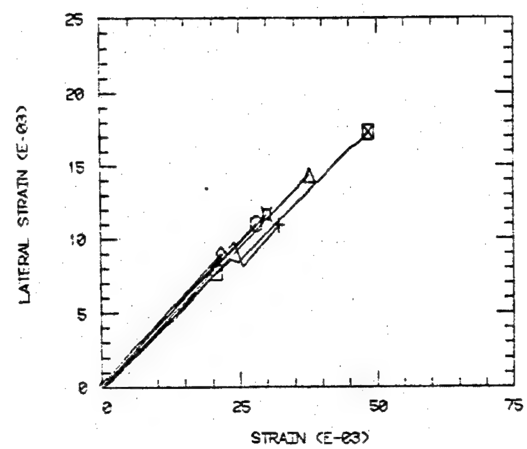
1826 NEAT, TENSION, 82 C, WET



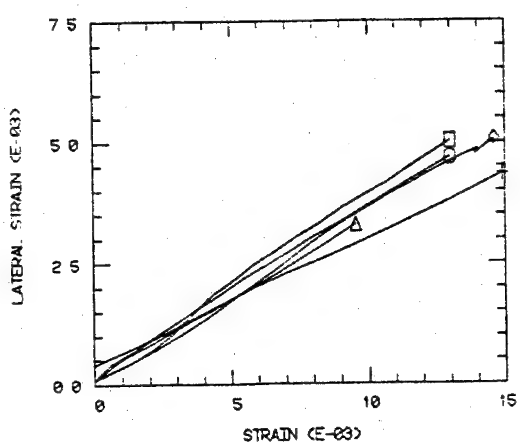
1826 NEAT, TENSION, 121 C, WET



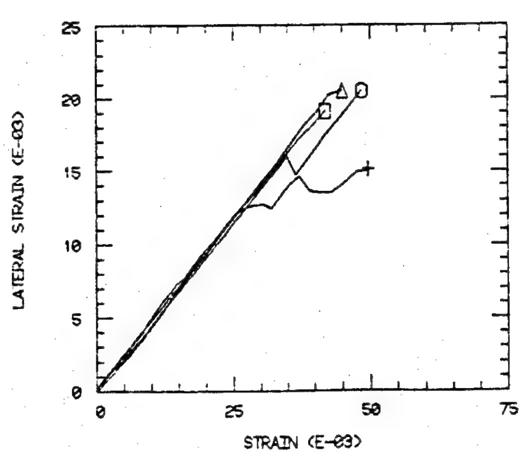
1806 NEAT, TENSION, 23 C, DRY



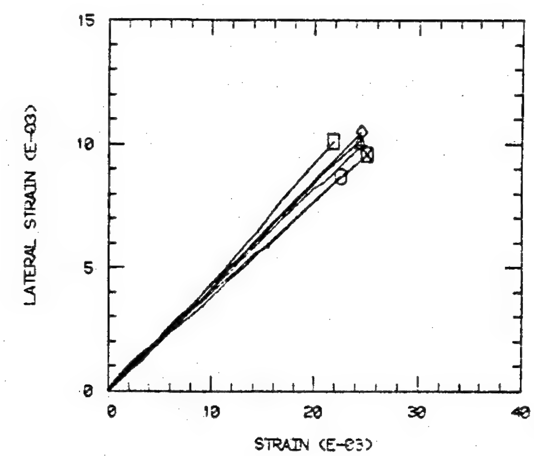
4901-B NEAT, POISSONS, 23 C, DRY



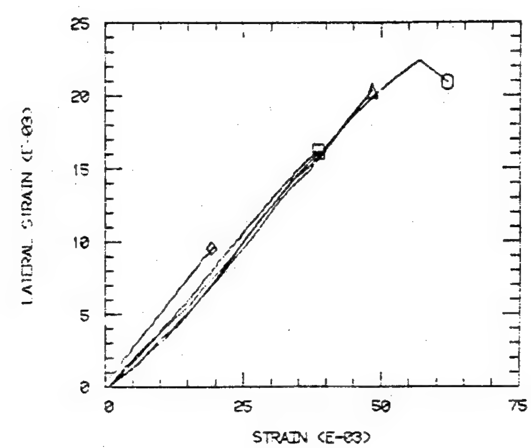
1806 NEAT, POISSONS, 82 C, DRY



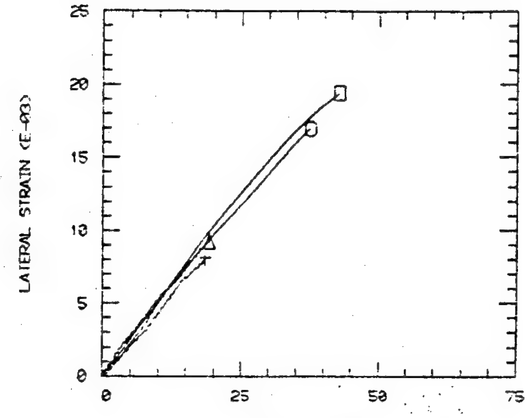
4901 MPDA, POISSONS, 80 C, DRY



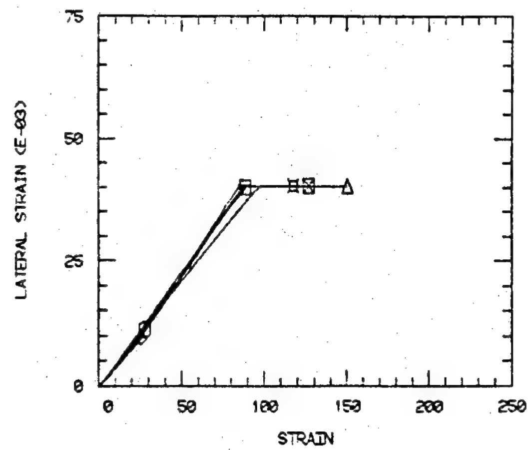
1805 NEAT, POISSONS, 121 C, DRY



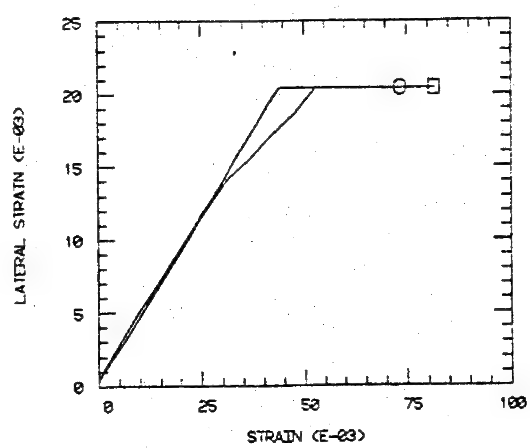
1805 NEAT, POISSONS, 121 C, DRY



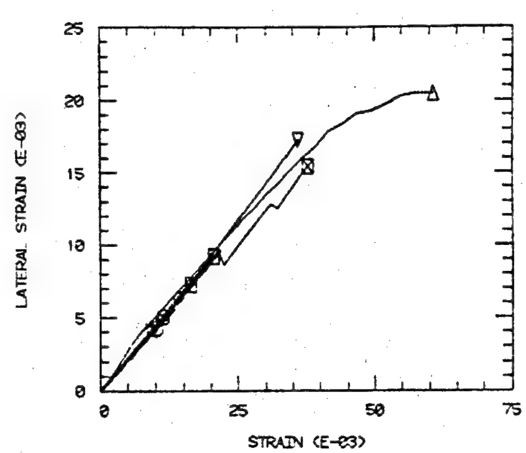
4901 MPDA, POISSONS, 100 C, DRY



4901-B NEAT, POISSONS, 121 C, DRY



1806 NEAT, POISSONS, 23 C, WET



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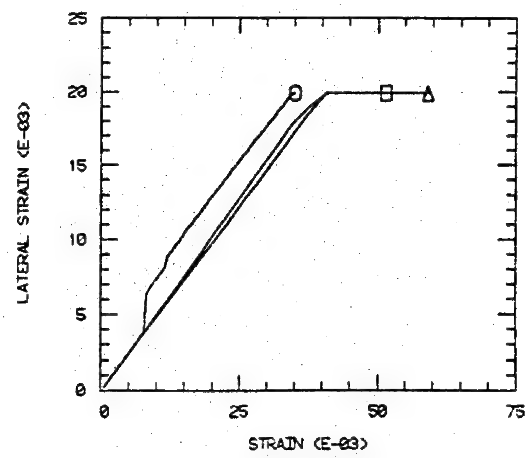

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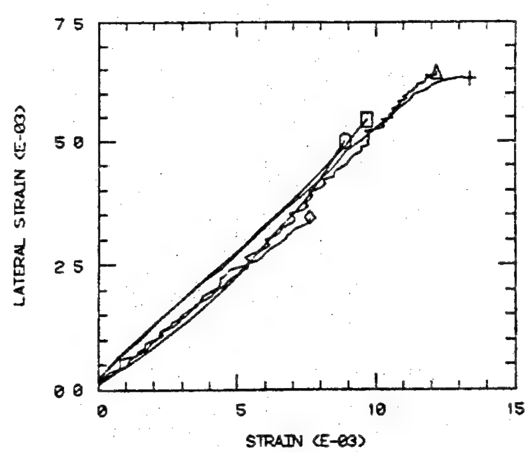
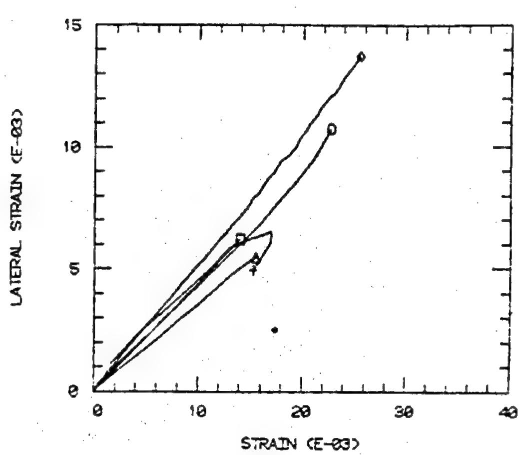
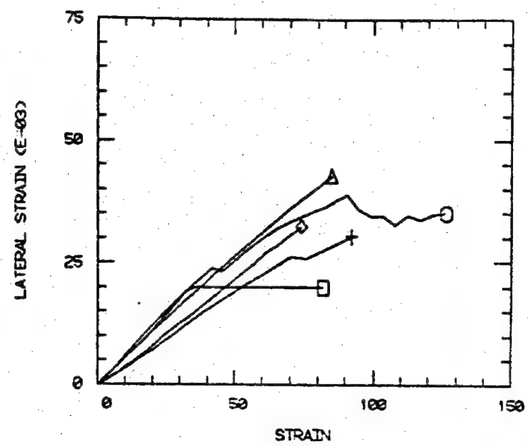


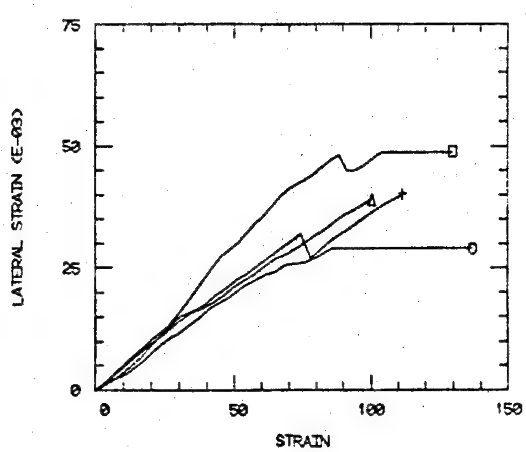
4901 MPDA NEAT, POISSONS, 60 C, WET



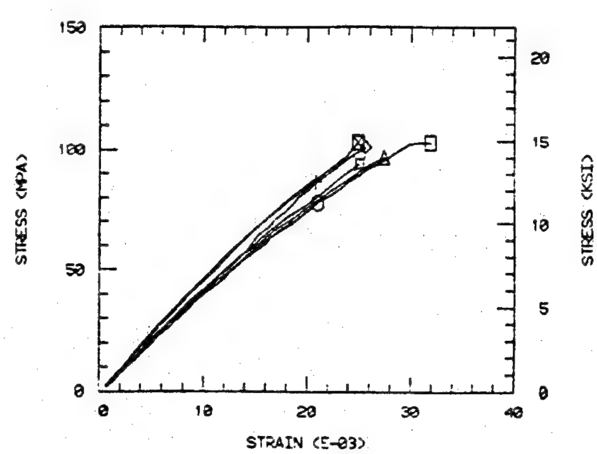
1806 NEAT, POISSONS, 82 C, WET



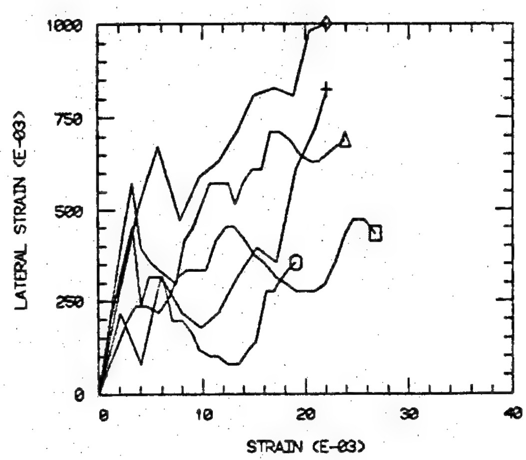
1805 NEAT, POISSONS, 121 C, WET



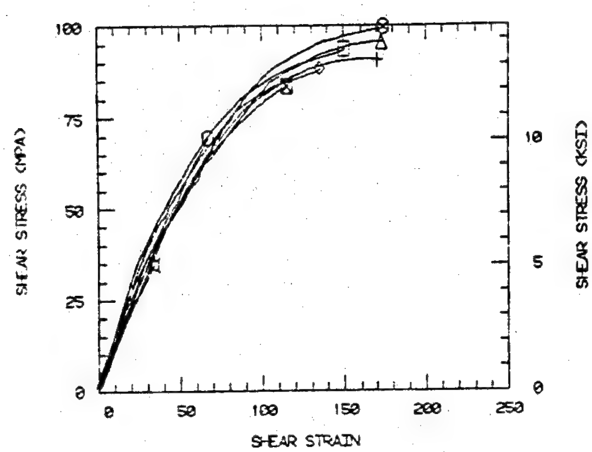
BP907 NEAT, TENSION, -80 C, DRY



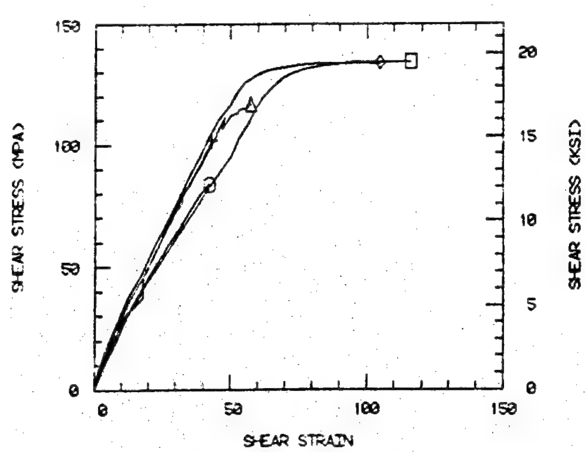
BP907 NEAT, POISSONS, -80 C, DRY



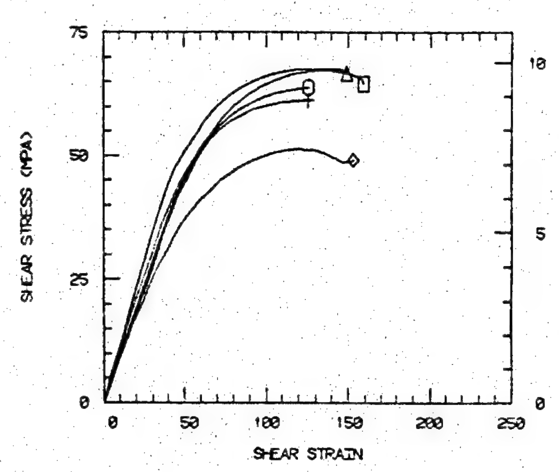
1805 NEAT, SHEAR(TORS), 23 C, DRY



4901-B NEAT, SHEAR(TORS), 23 C, DRY



1806 NEAT, SHEAR(TORS), 82 C, DRY



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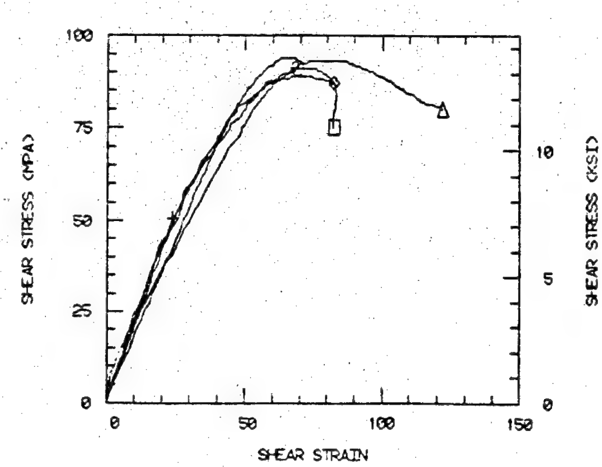

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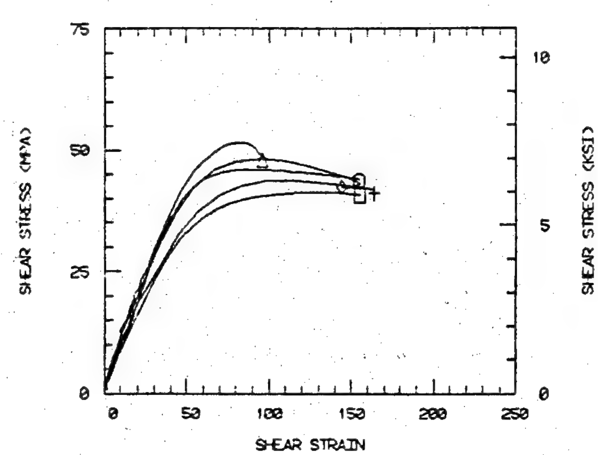

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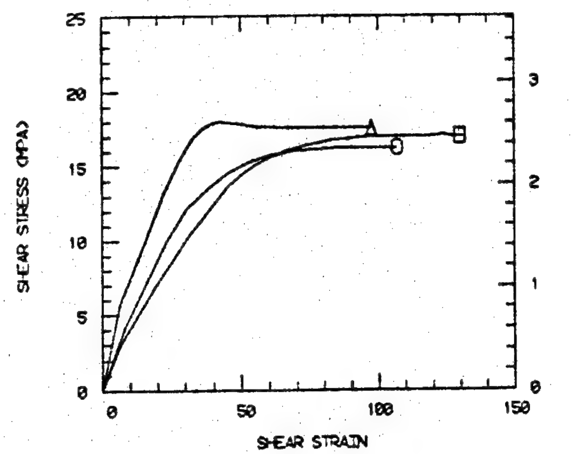

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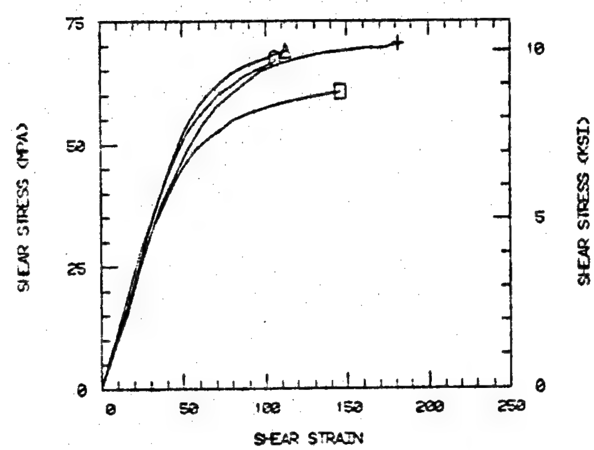

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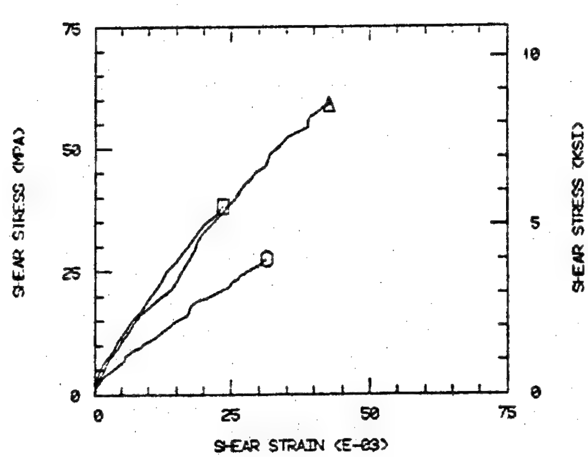

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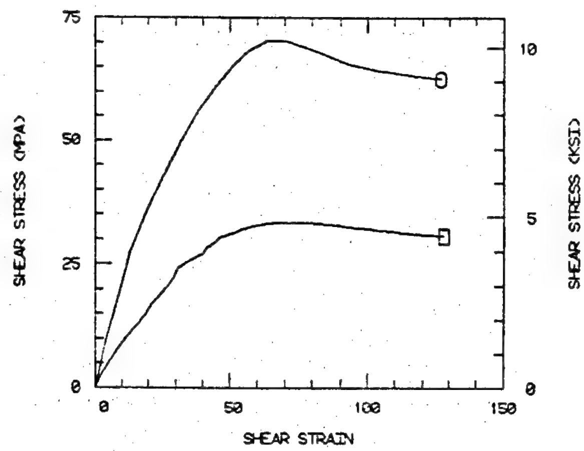
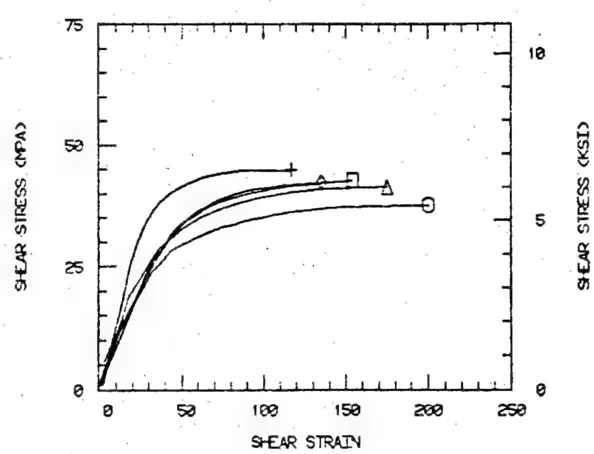
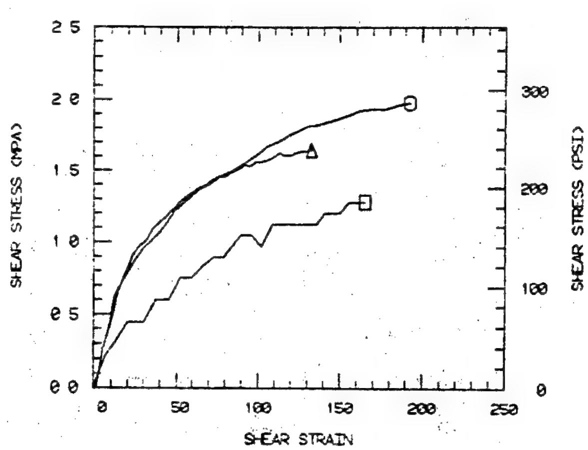


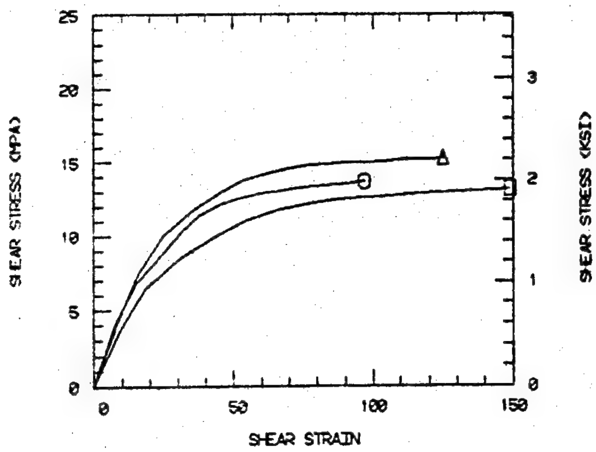
1806 NEAT, SHEAR(TORS), 82 C, WET



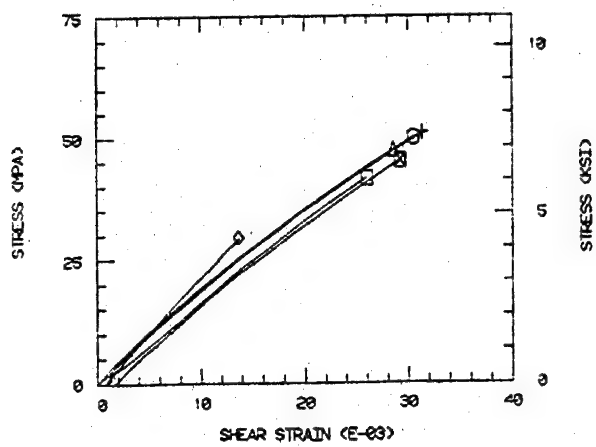
4901-B NEAT, SHEAR(TORS), 82 C, WET



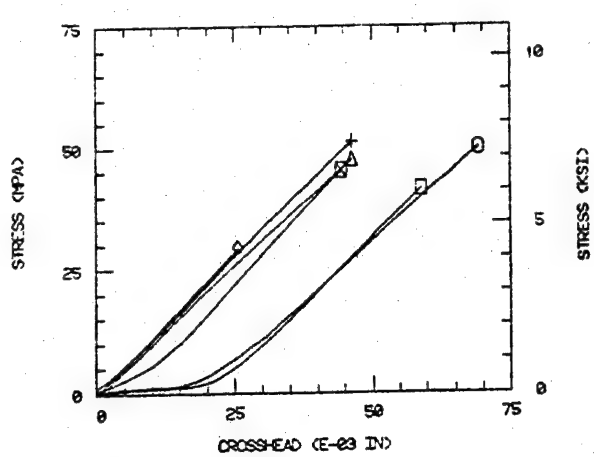
1806 NEAT, SHEAR(TORS), 121 C, WET



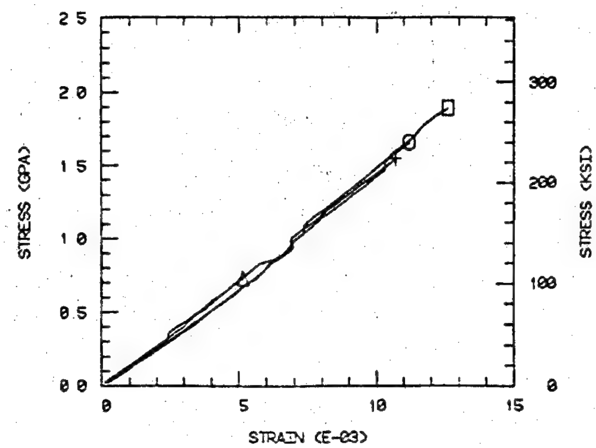
BP907 NEAT, SHEAR, -80 C, DRY



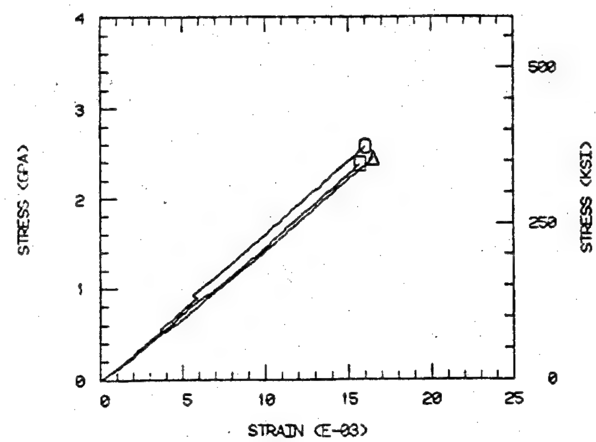
BP907 NEAT, SHEAR, -80 C, DRY



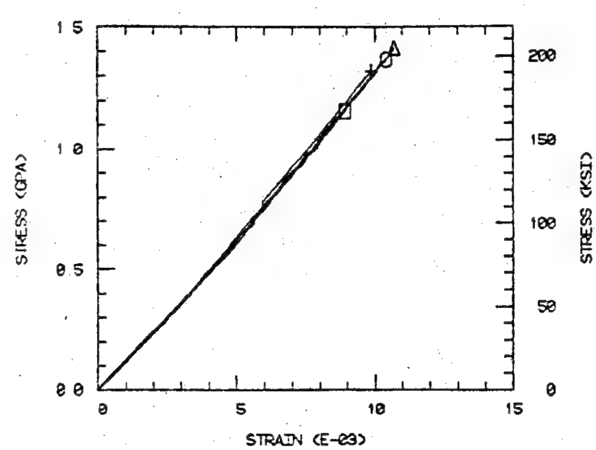
AS4/3502, AXIAL TENS, 23 DEG C, DRY



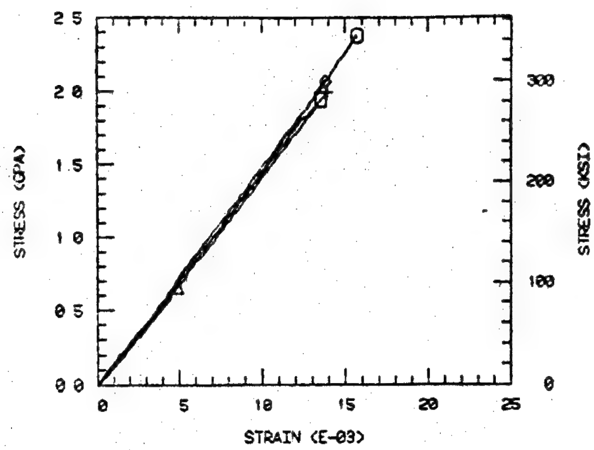
AS6/5245C, AXIAL TEN, 23 DEG C, DRY



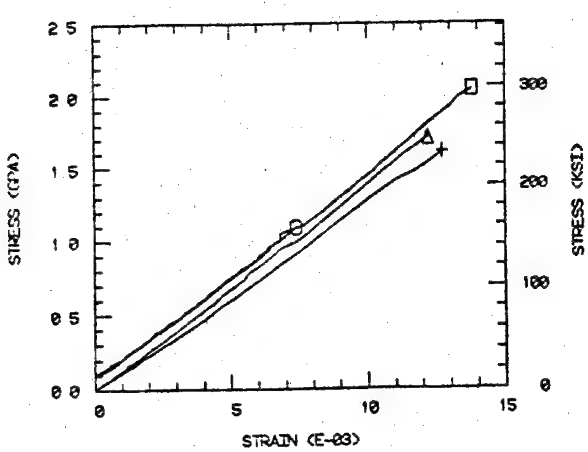
T300/BP907, AXIAL TEN, 23 DEG C,DRY



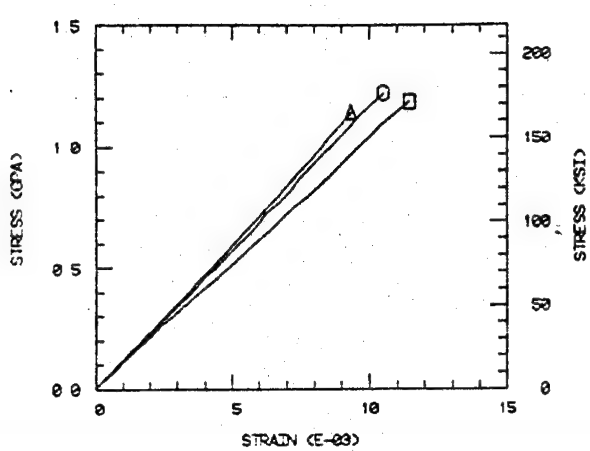
C6000/1805, AXIAL TEN, 23 DEG C, DRY



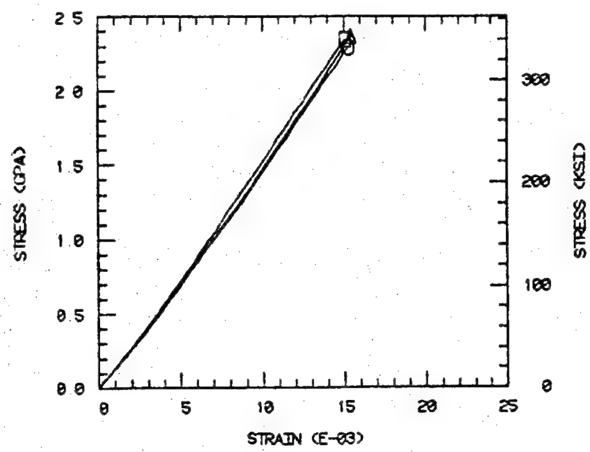
AS4/3502, AXIAL TEN, 100 C, DRY



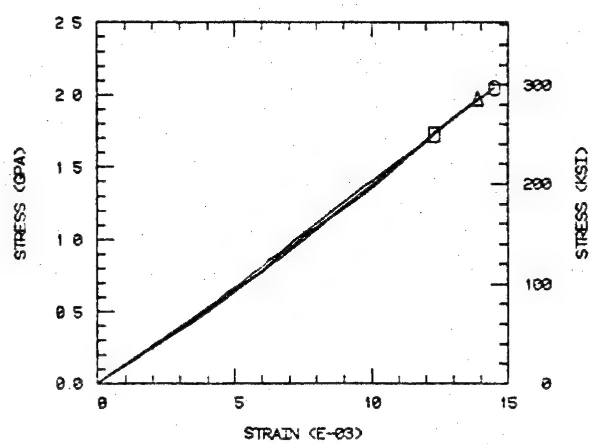
T300/BP907, AXIAL TEN, 100 C, DRY



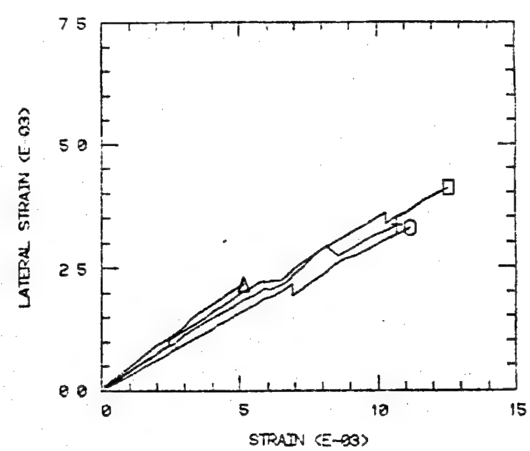
AS6/5245C, AXIAL TEN, 100 C, DRY



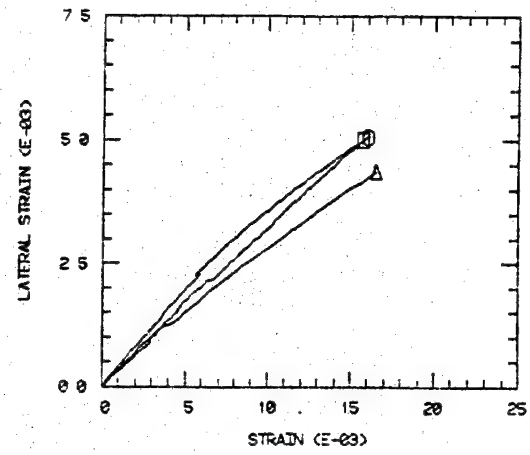
C6000/1806, AXIAL TEN, 100 C, DRY



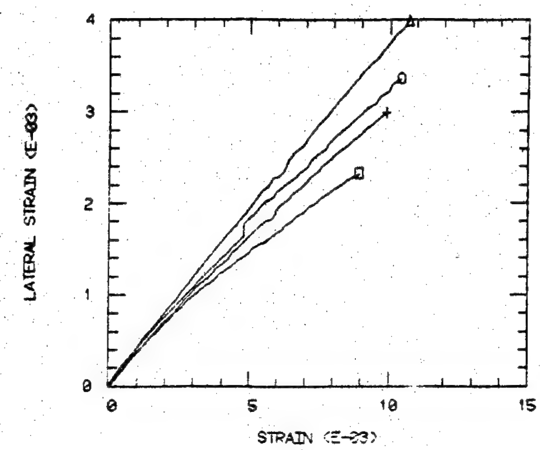
AS4/3502, POISSONS, 23 DEG C, DRY



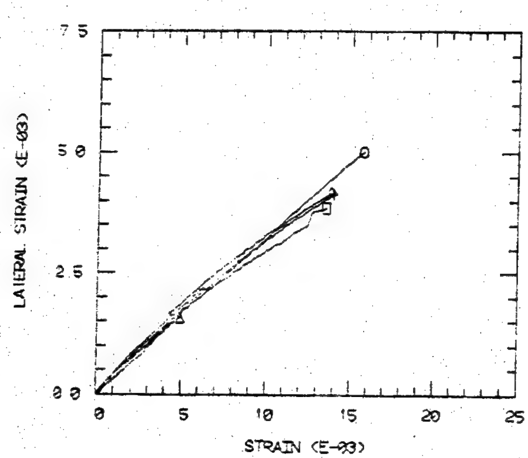
AS6/5245C, POISSONS, 23 DEG C, DRY



T300/907, POISSONS, 23 DEG C, DRY



C6000/1806, POISSONS, 23 DEG C, DRY



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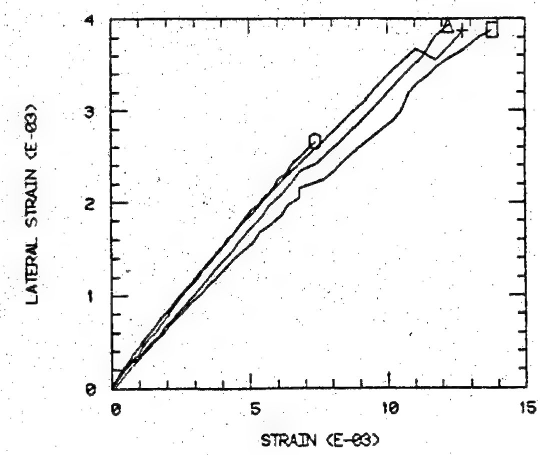
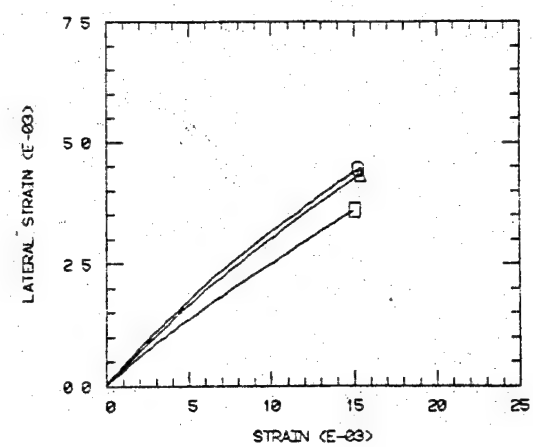
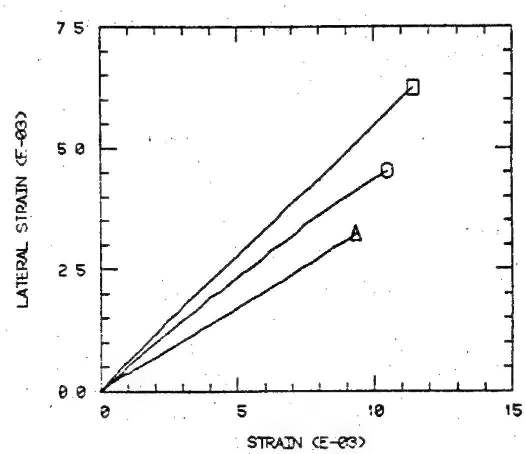


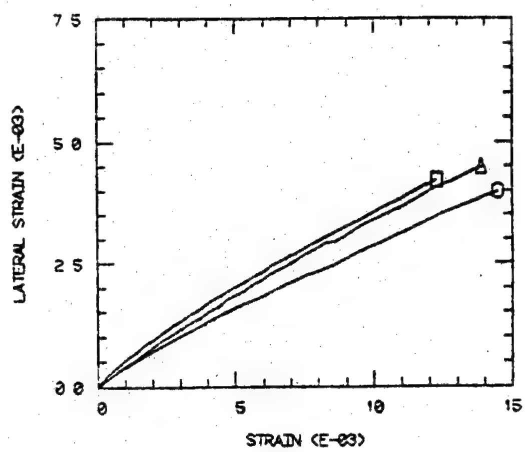
AS6/5245C, POISSONS, 100 C, DRY



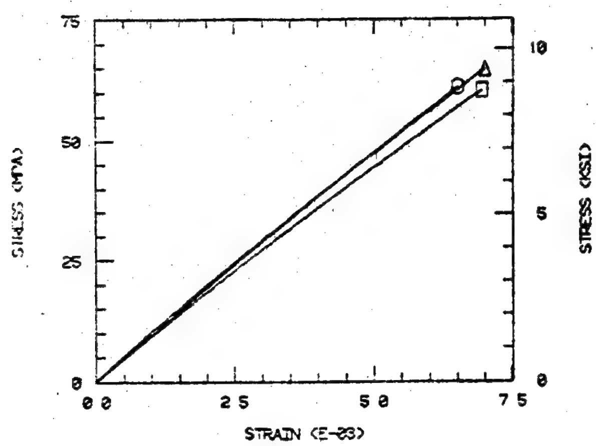
T300/BP907, POISSONS, 100 C, DRY



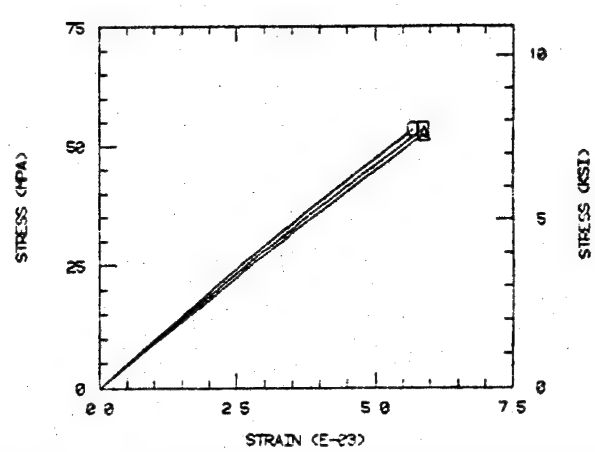
C6000/1806, POISSONS, 100 C, DRY



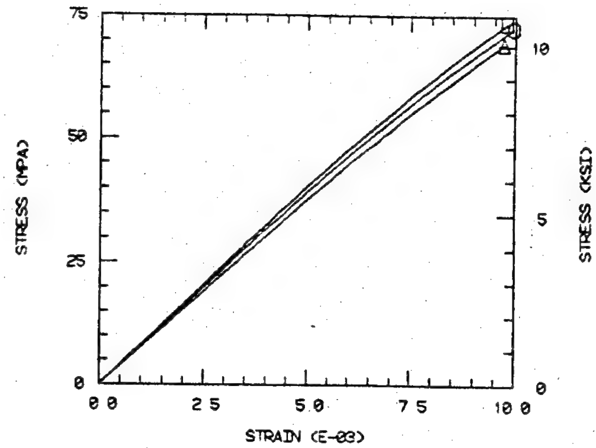
AS4/3502, TRANVERSE TEN, 23 C, DRY



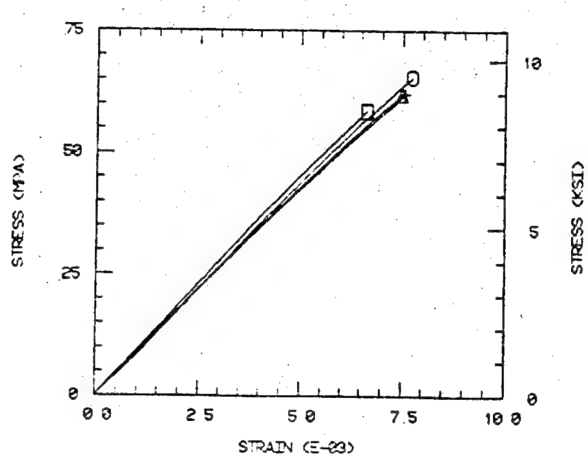
AS6/5245C, TRANSVERSE TEN, 23 C, DRY



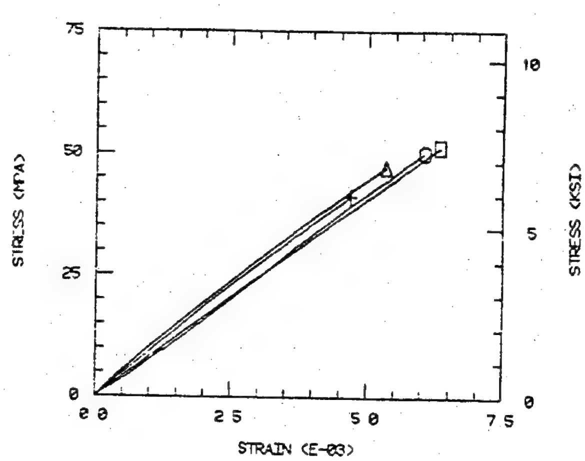
T300/BP907, TRANSVERSE TEN, 23 C, DRY



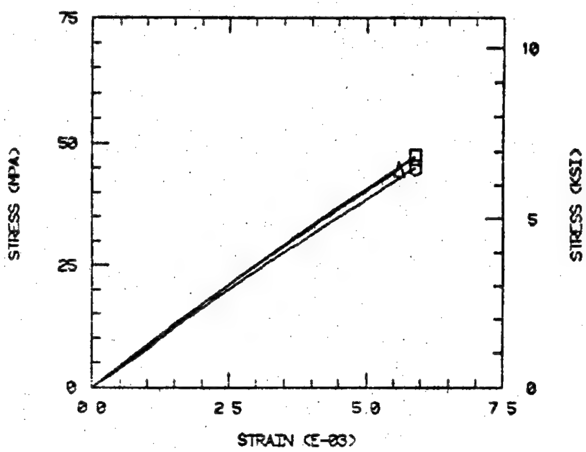
C6000/1806, TRANSVERSE TEN, 23 C, DRY



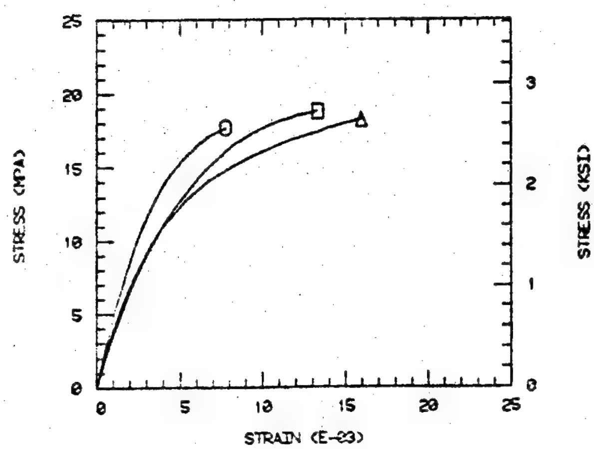
AS4/3502, TRANSVERSE TEN, 100 C, DRY



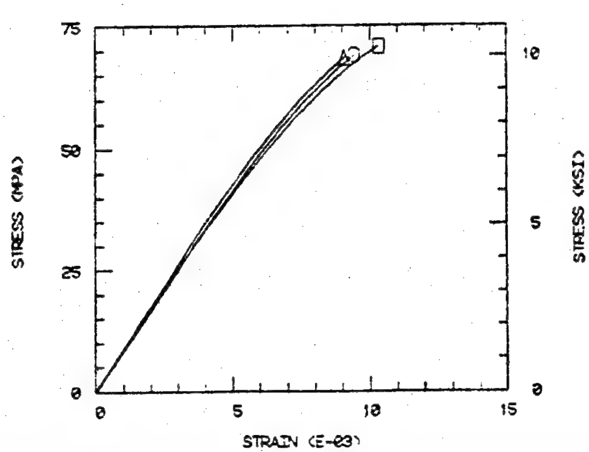
AS6/5245C, TRANSVERSE TEN, 100 C, DRY



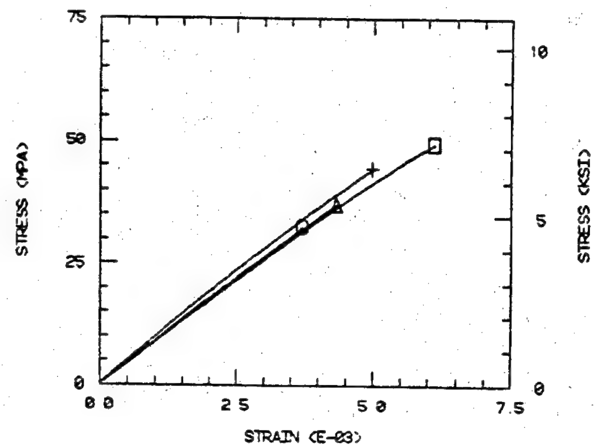
T300/BP907, TRANSVERSE TEN, 100 C, DRY



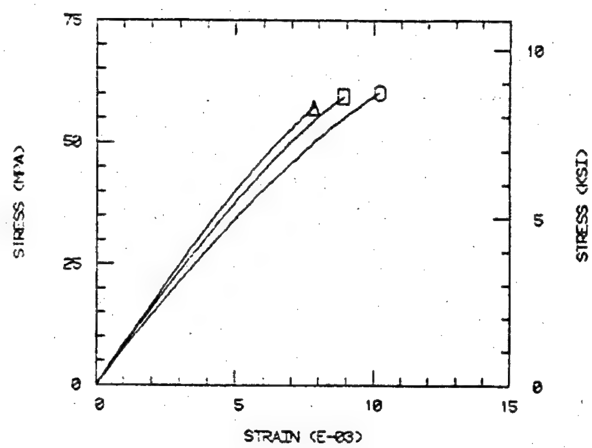
C6000/1806, TRANSVERSE TEN, 100 C, DRY



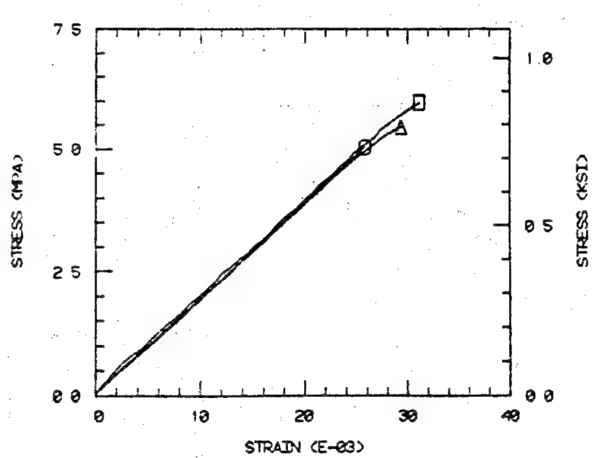
AS4/3502, TRANSVERSE TEN, 121 C, DRY



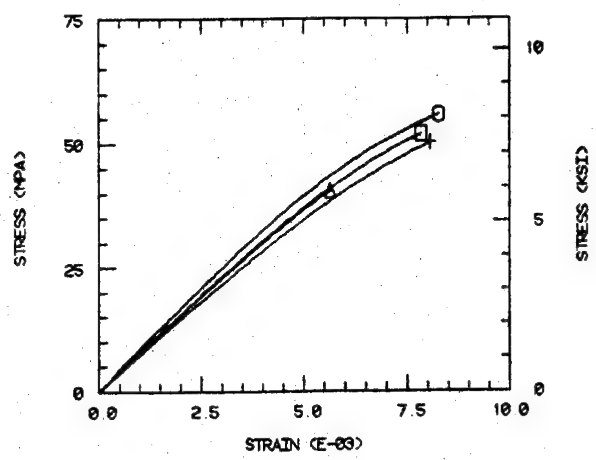
AS6/5245C, TRANSVERSE TEN, 121 C, DRY



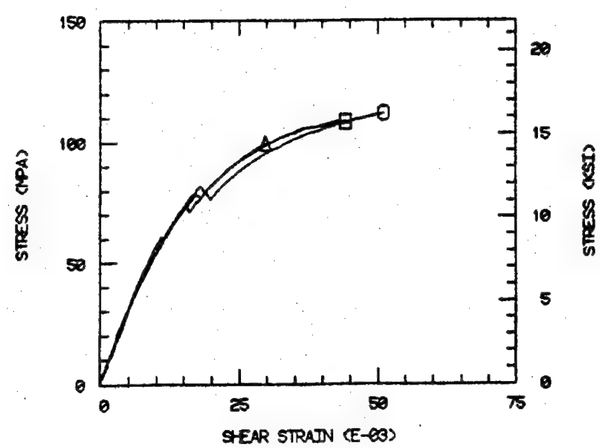
T300/BP907, TRANSVERSE TEN, 121 C, DRY



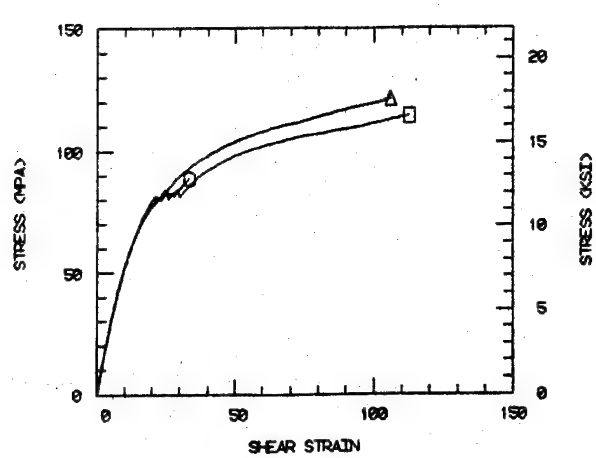
C6000/1806, TRANSVERSE TEN. 121 C. DRY



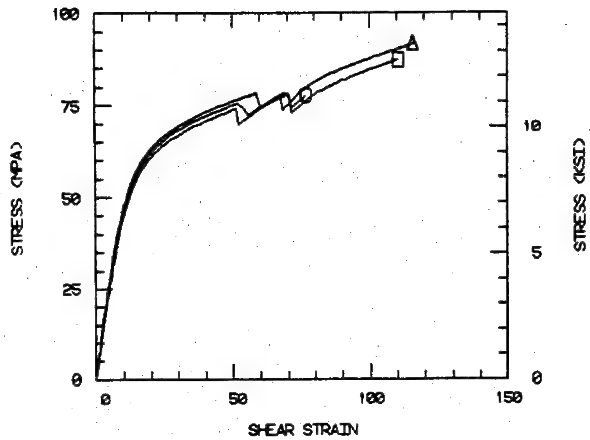
AS4/3502, IOSIPESCU, 23 C, DRY



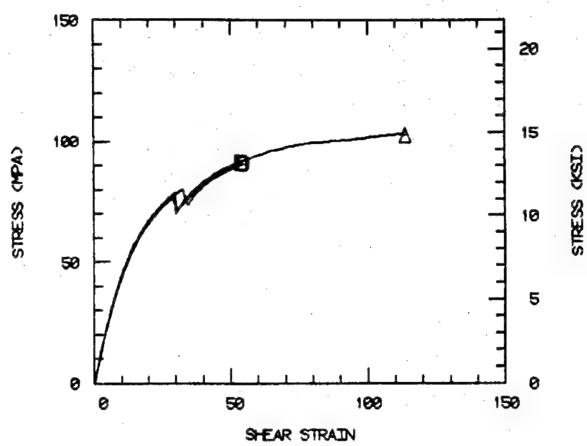
AS6/5245, IOSIPESCU, 23 C, DRY



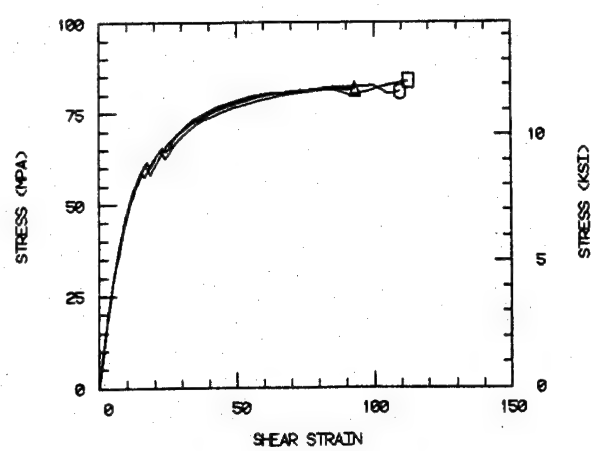
T300/BP907, IOSIPESCU, 23 C, DRY



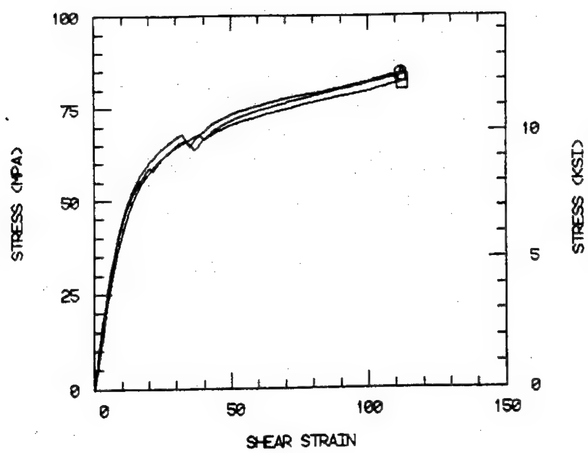
C6000/1806, IOSIPESCU, 23 C, DRY



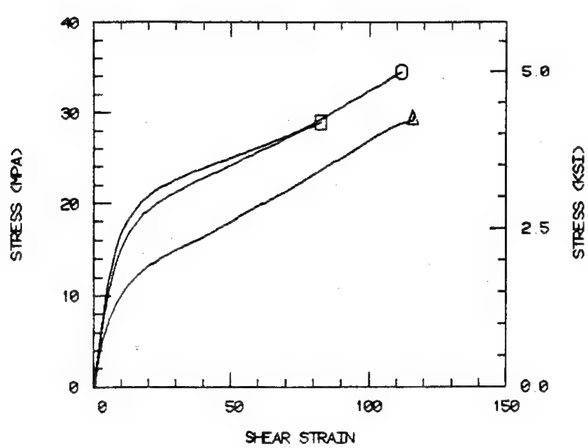
AS4/3502, IOSIPESCU, 23 C, DRY



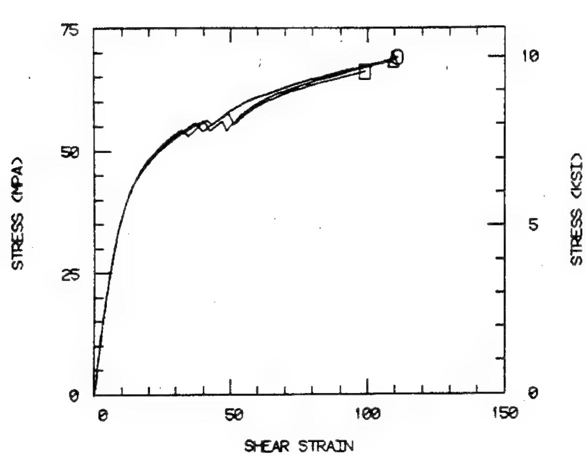
AS6/5245, IOSIPESCU, 100 C, DRY



T300/BP907, IOSIPESCU, 100 C, DRY



C6000/1806, IOSIPESCU, 100 C, DRY



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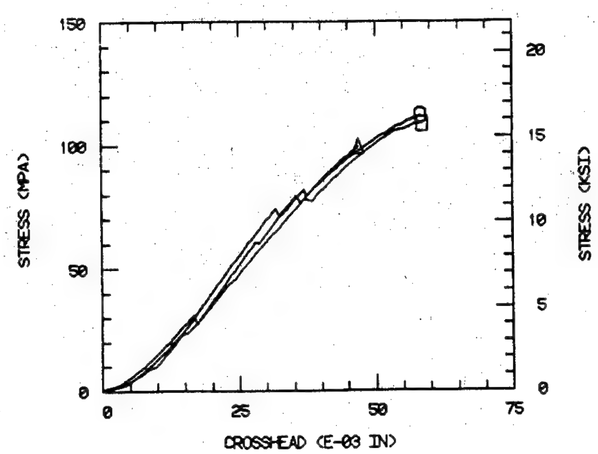

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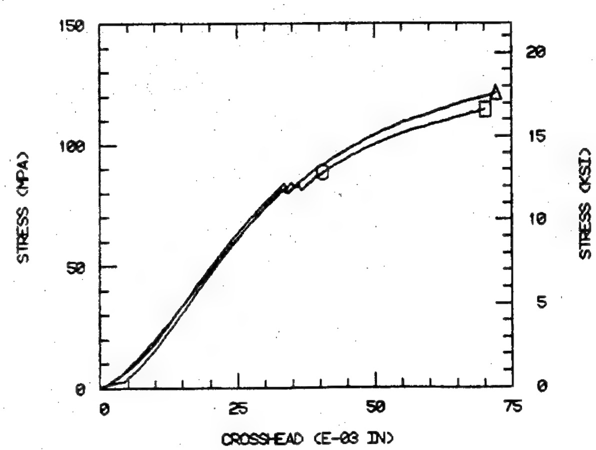

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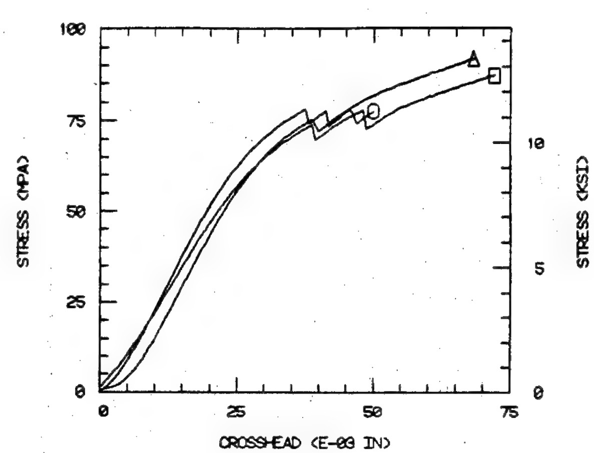
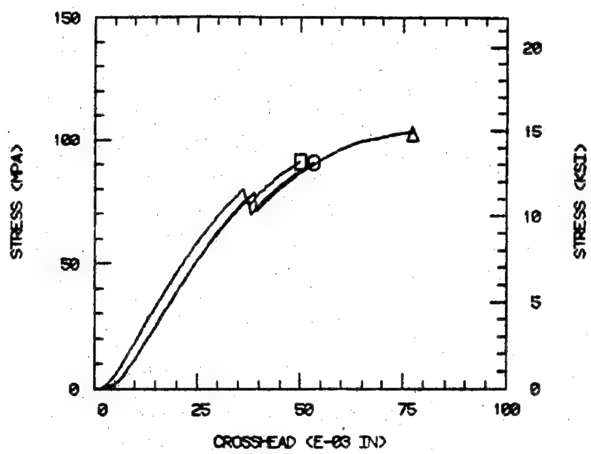
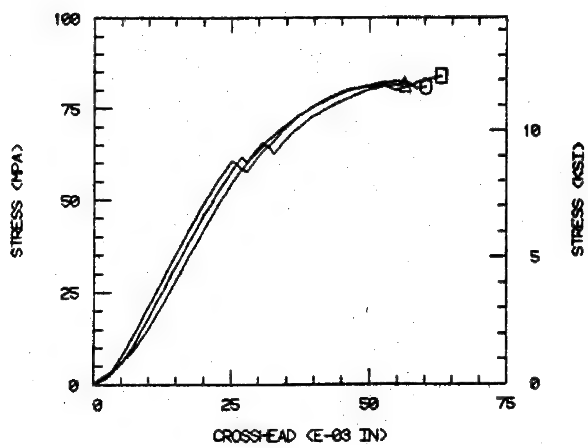


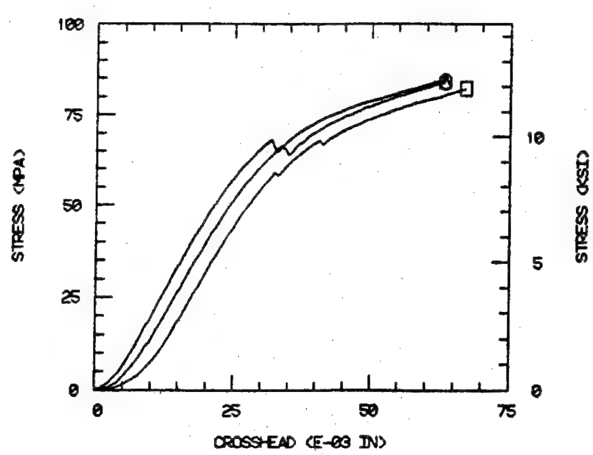
C6000/1806, IOSIPESCU, 23 C, DRY



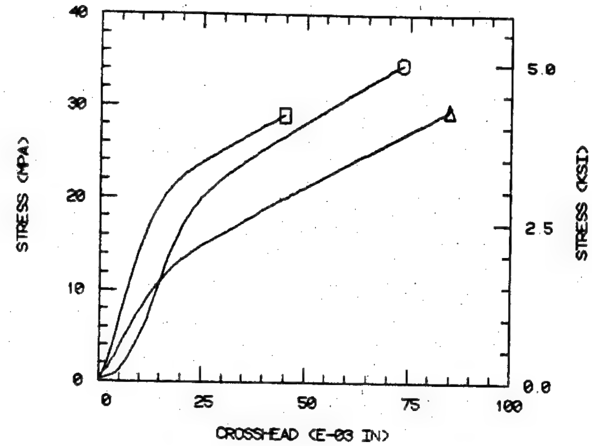
AS4/3502, IOSIPESCU100 C, DRY



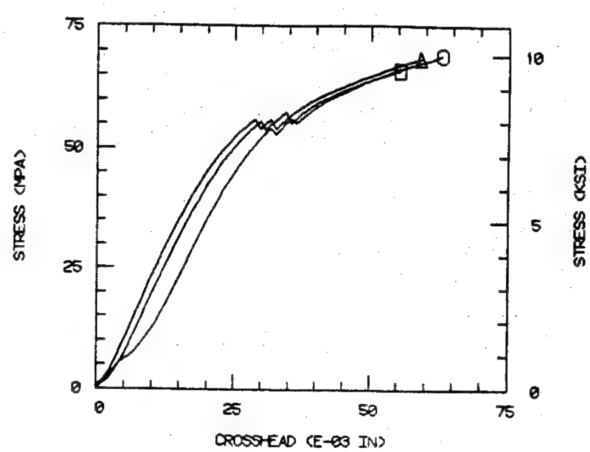
AS6/5245, IOSIPESCU, 100 C, DRY



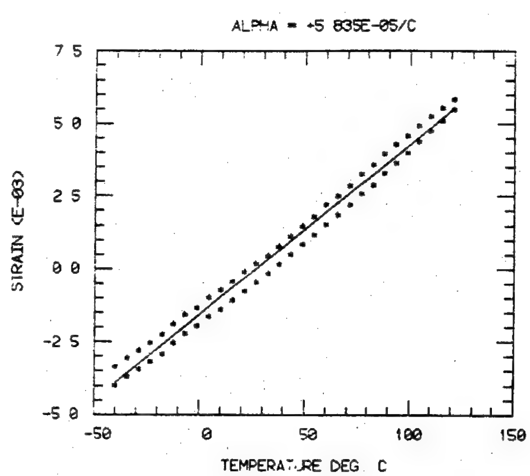
T300/BP907, IOSIPESCU, 100 C, DRY



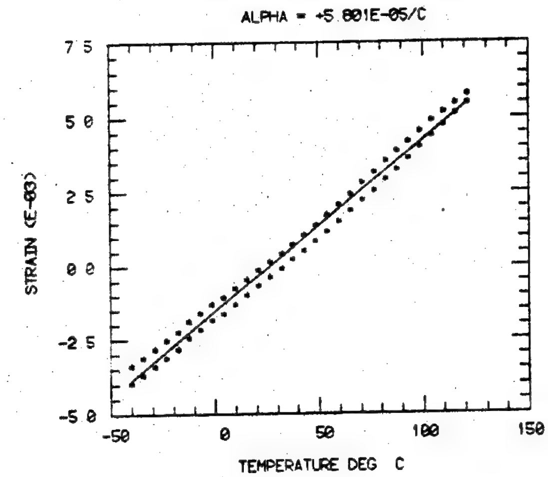
C6000/1806, IOSIPESCU, 100 C, DRY



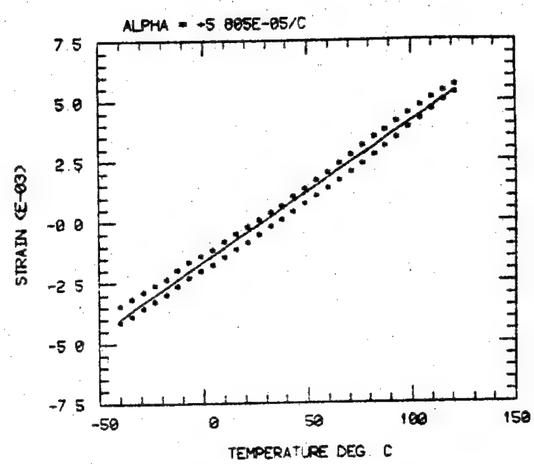
CYCOM 1806 NEAT EPOXY DRY NO 1



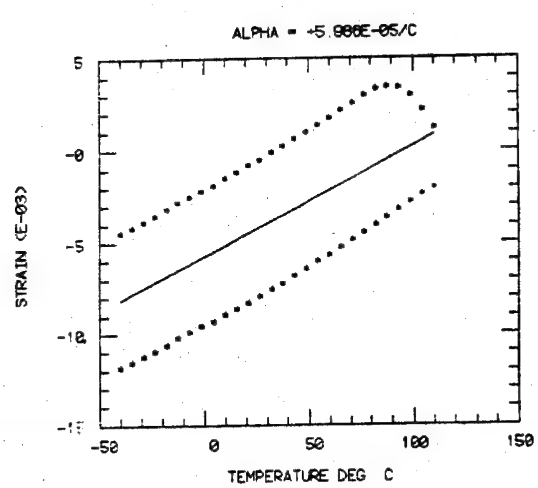
CYCOM 1806 NEAT EPOXY DRY NO 2



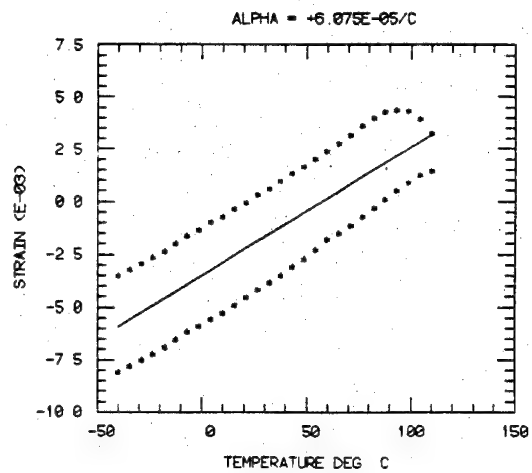
CYCOM 1806 NEAT EPOXY DRY NO. 3



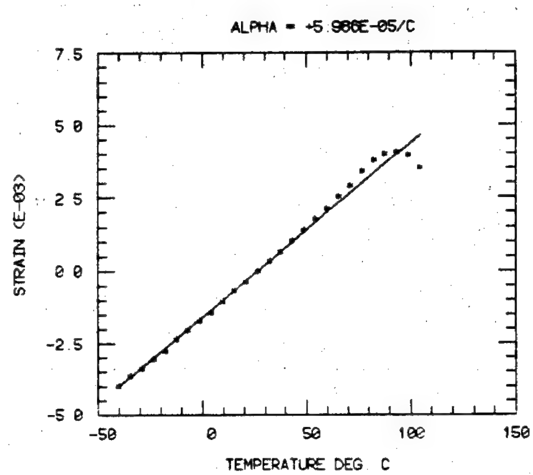
CYCOM 1806 NEAT EPOXY WET NO 1



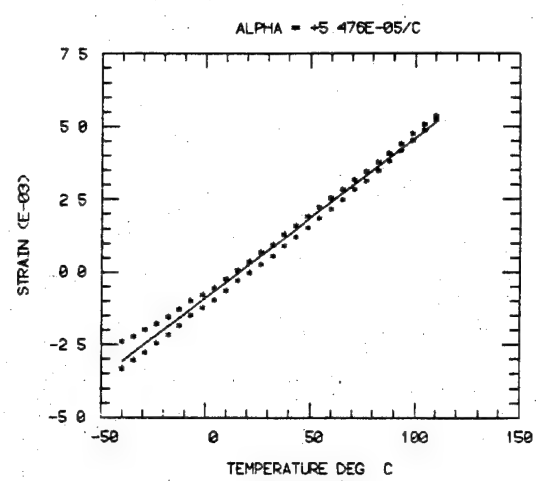
CYCOM 1806 NEAT EPOXY WET NO 2



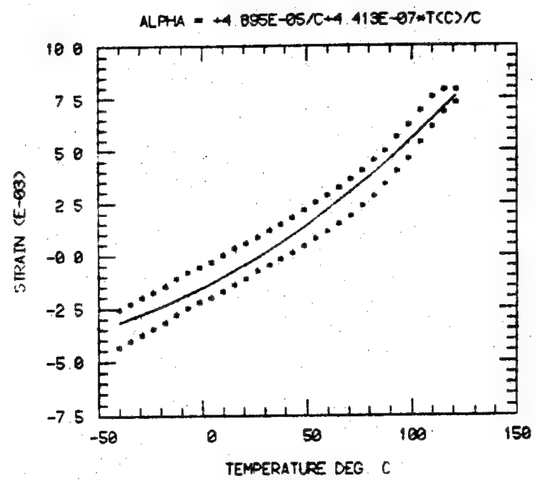
CYCOM 1806 NEAT EPOXY WET NO 3



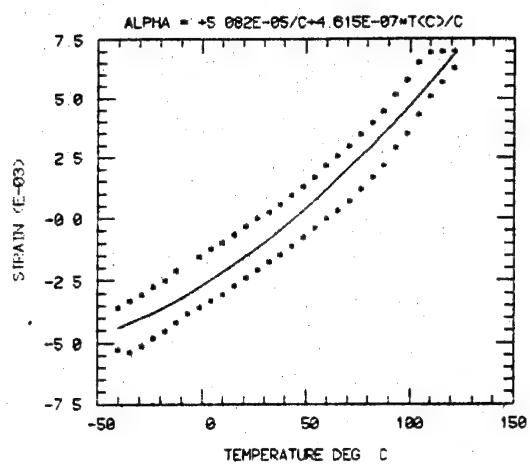
CYCOM 1806 NEAT EPOXY WET NO 4



4901B(MPDA) NEAT EPOXY DRY NO. 1



4901B(MPDA) NEAT EPOXY DRY NO 2



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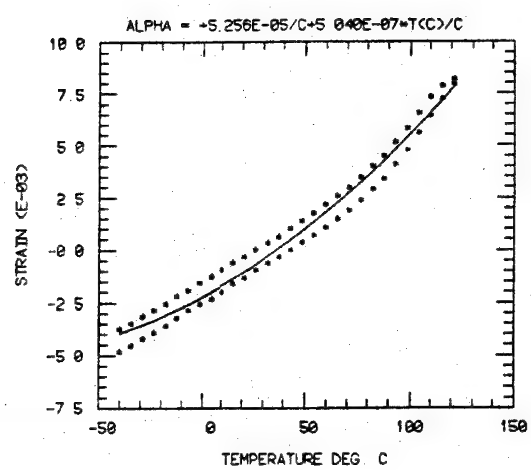

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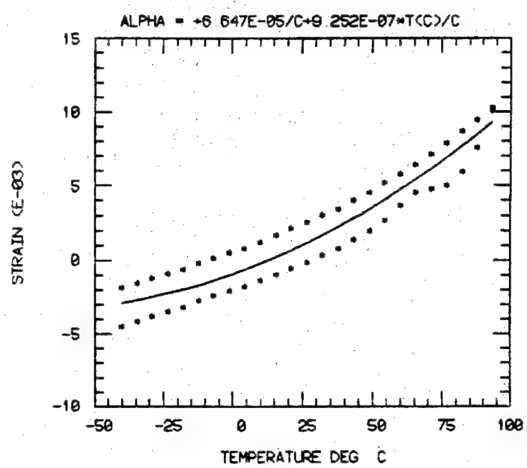

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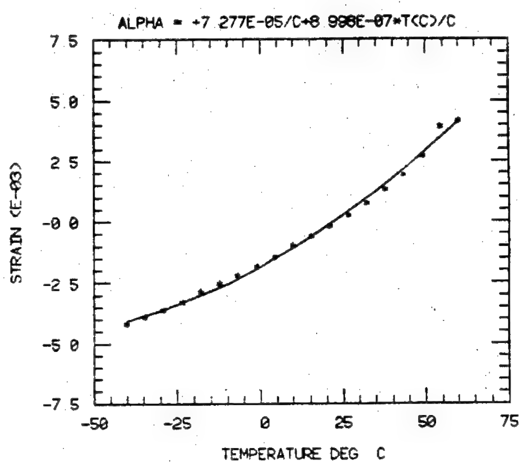
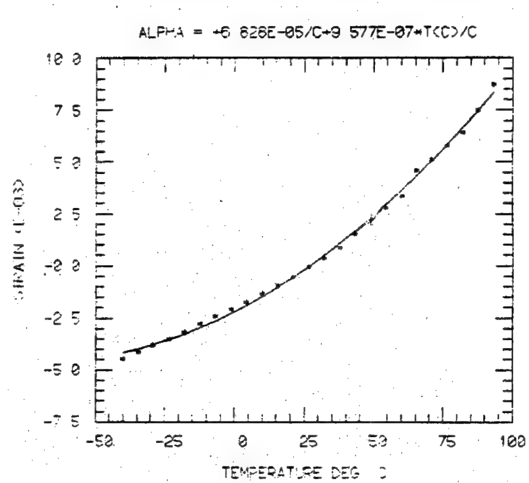
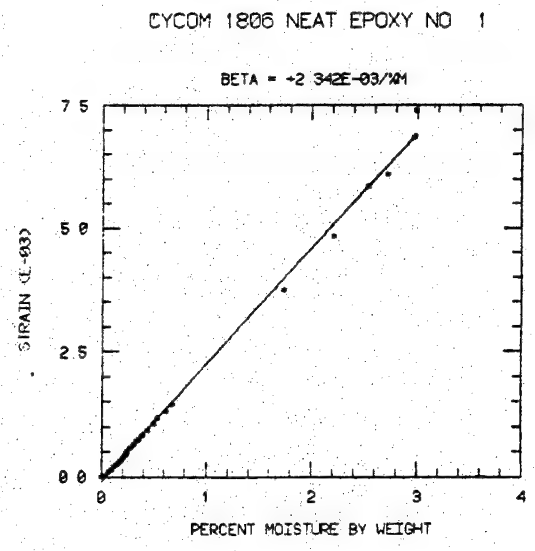
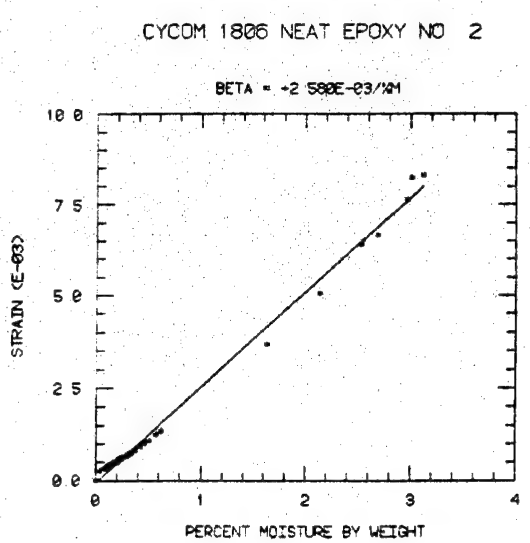
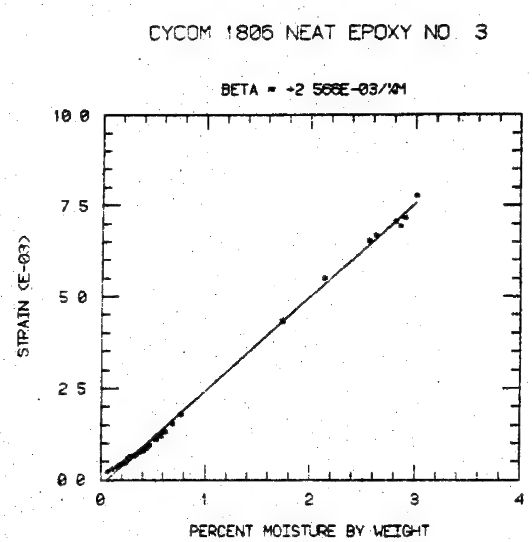


4901B(MPDA) NEAT EPOXY WET NO. 3

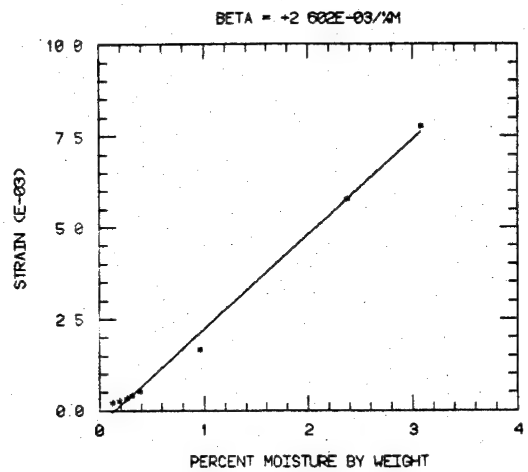



CYCOM 1806 NEAT EPOXY NO 1
BETA = +2 342E-03/%M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
7 5
5 0
2 5
0 0
0
1
2
3
4

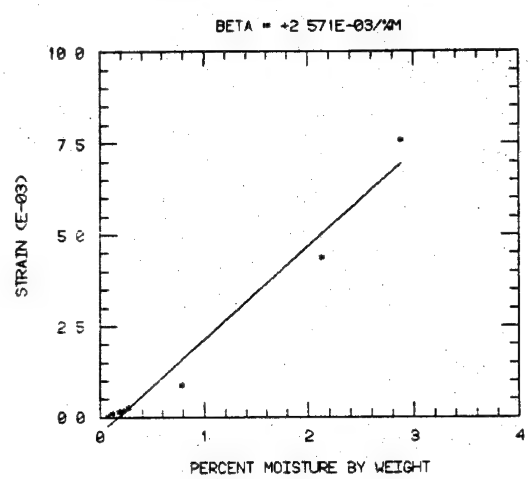

CYCOM 1806 NEAT EPOXY NO 2
BETA = +2 580E-03/%M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
10 0
7 5
5 0
2 5
0 0
0
1
2
3
4


CYCOM 1806 NEAT EPOXY NO 3
BETA = +2 566E-03/%M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
10 0
7 5
5 0
2 5
0 0
0
1
2
3
4

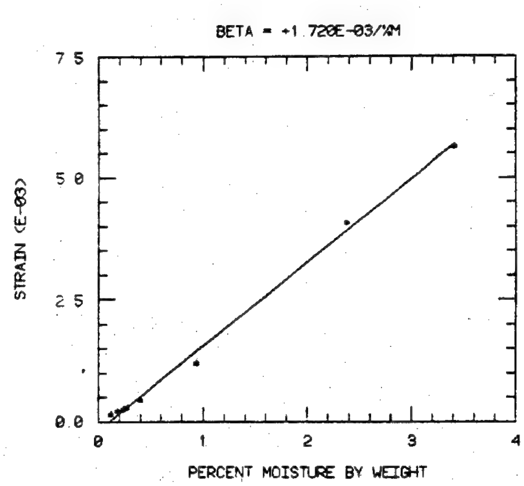
CYCOM 1806 NEAT EPOXY NO 4



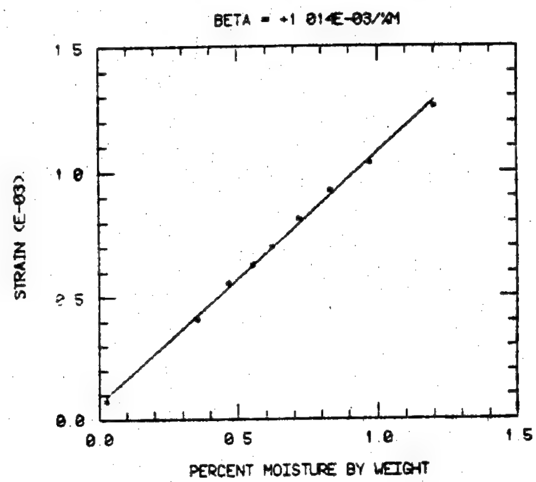
CYCOM 1806 NEAT EPOXY NO 5



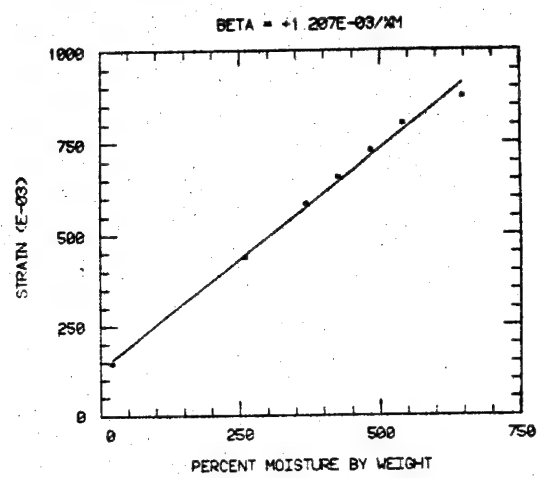
CYCOM 1806 NEAT EPOXY NO 6



4901B(MPDA) NEAT EPOXY NO 1



4901B(MPDA) NEAT EPOXY NO. 2



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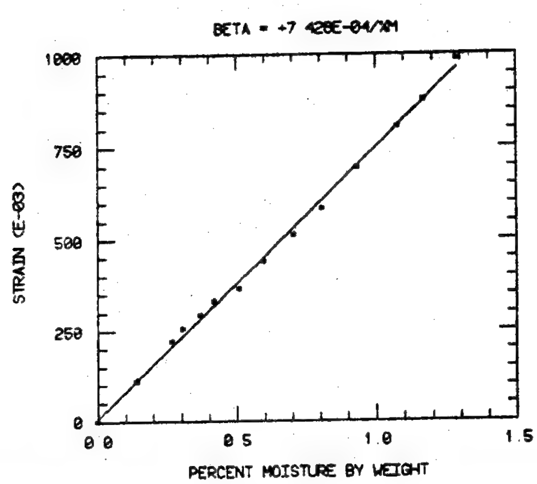

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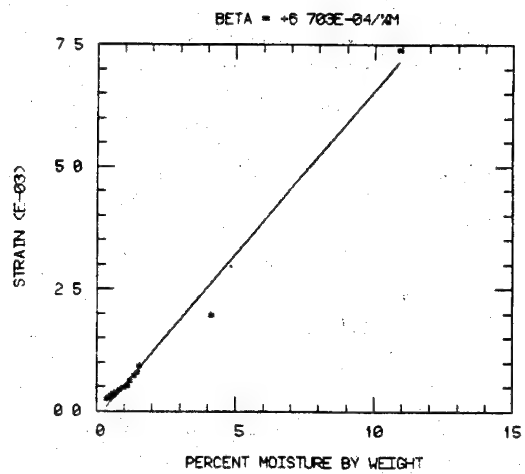
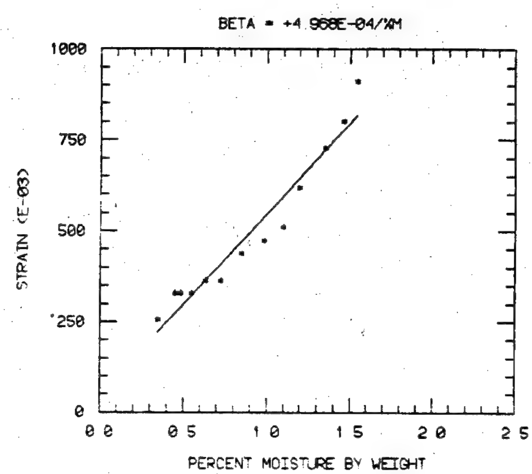
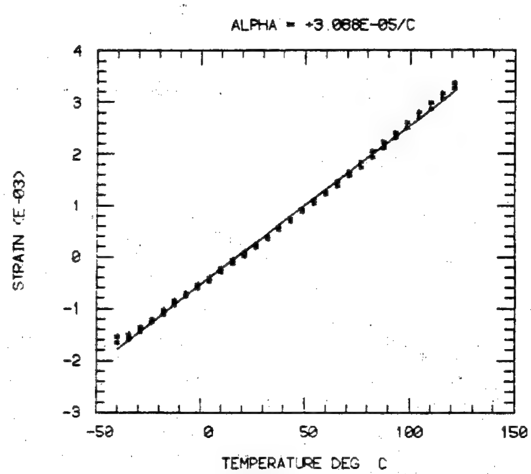


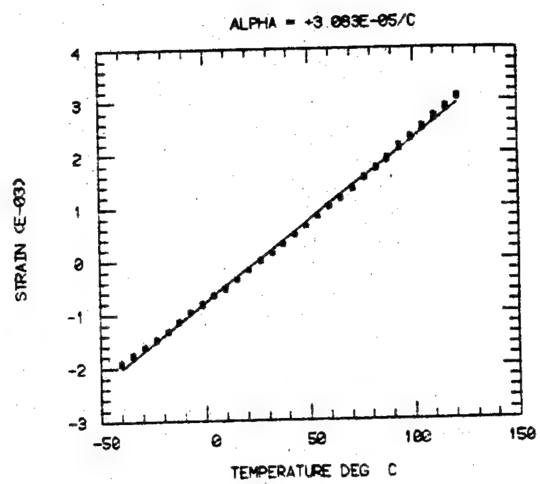
4901B(MPDA) NEAT EPOXY NO 5



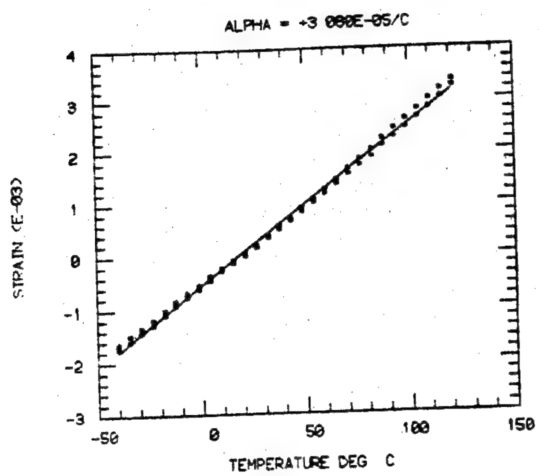
AS4/3502 90 DEG NO 1



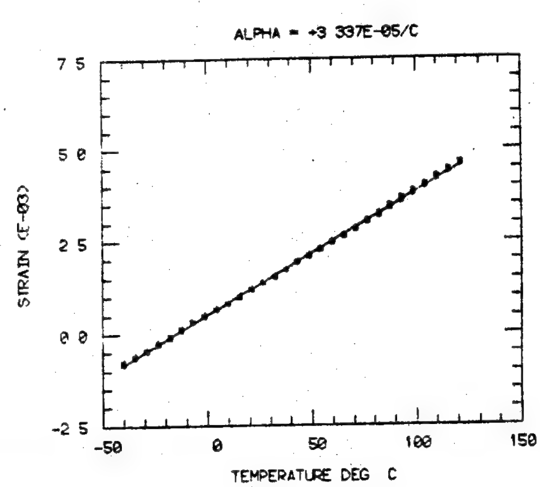
AS4/3502 90 DEG NO. 2



AS4/3502 90 DEG NO. 3

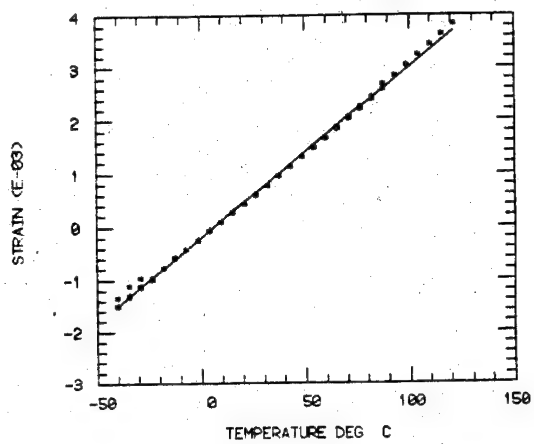


AS6/5245 90 DEG NO. 1



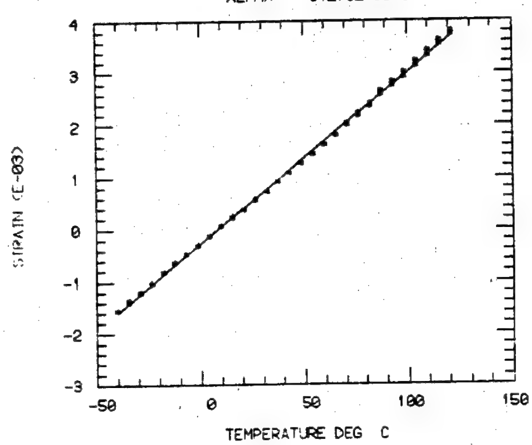
AS6/5245C 90 DEG NO 2

ALPHA = +3 218E-05/C



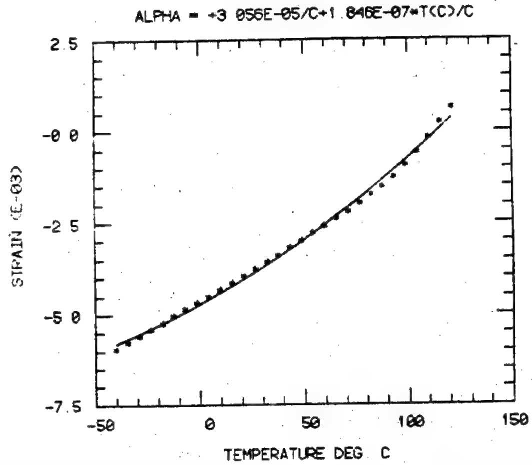
AS6/5245 90 DEG NO 3

ALPHA = +3.279E-05/C

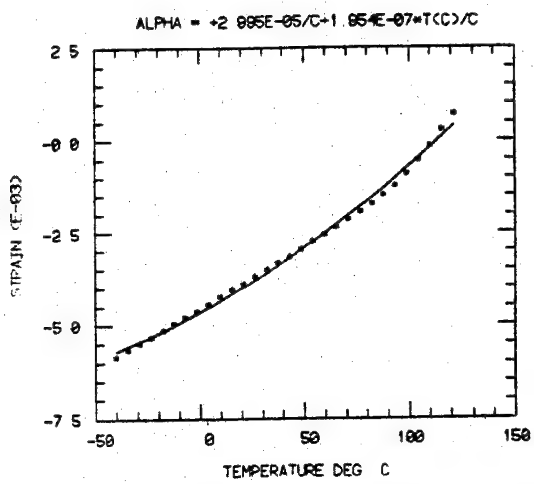


T300/BP907 90 DEG NO 1

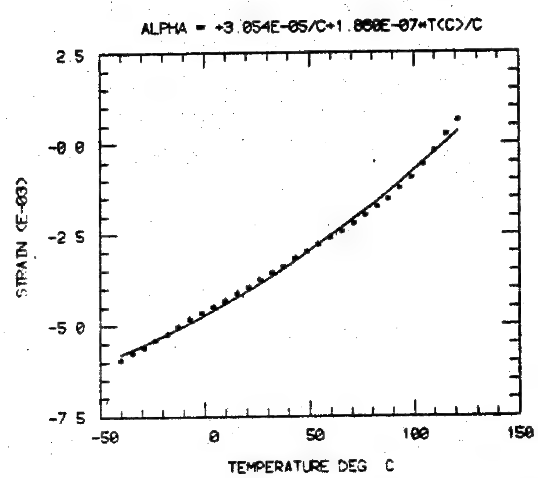
ALPHA = +3 056E-05/C+1 846E-07*T(C)/C



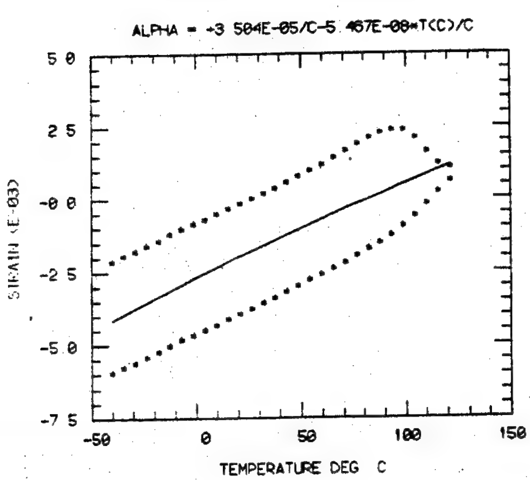
T300/BP907 90 DEG NO 2



T300/BP907 90 DEG NO 3



T300/BP907 90 DEG NO 1



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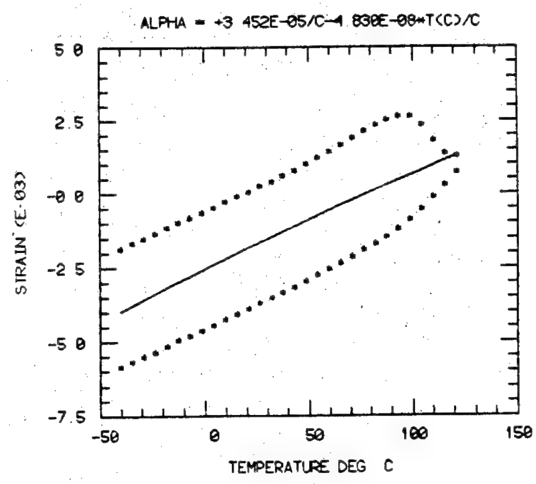
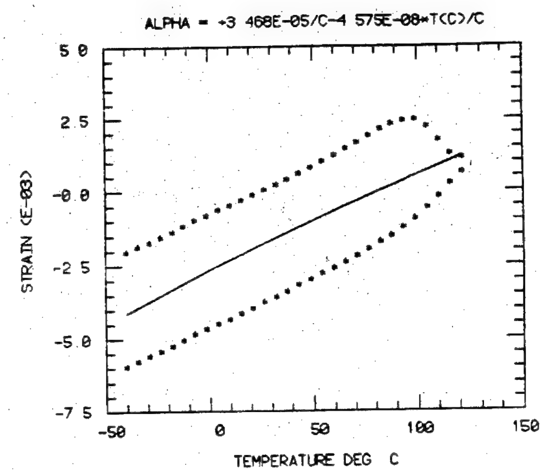
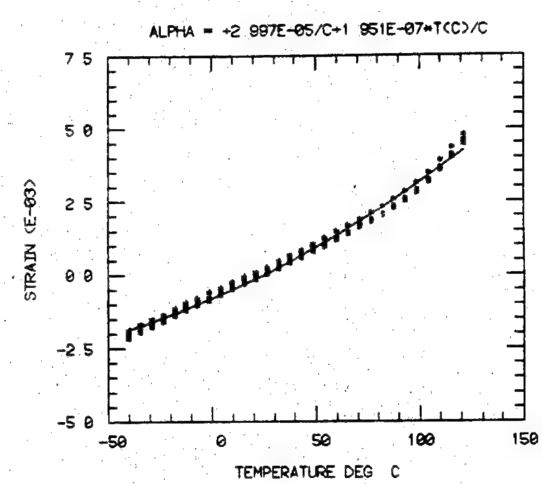


T300/BP907 90 DEG NO. 3



T300/BP907 90 DEG NO. 4



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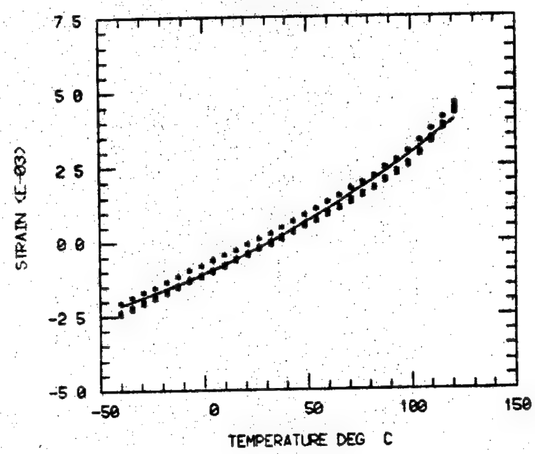

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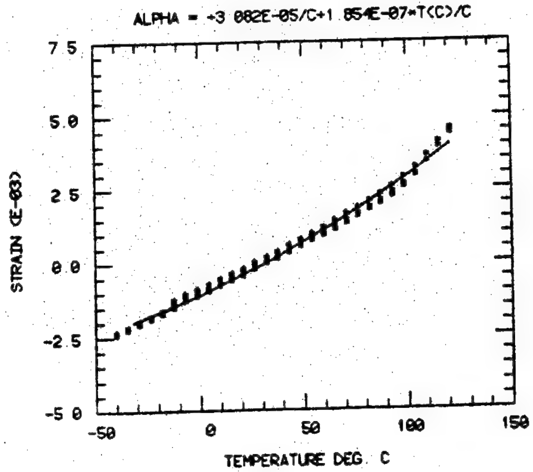

C6000/1806 90 DEG NO. 1

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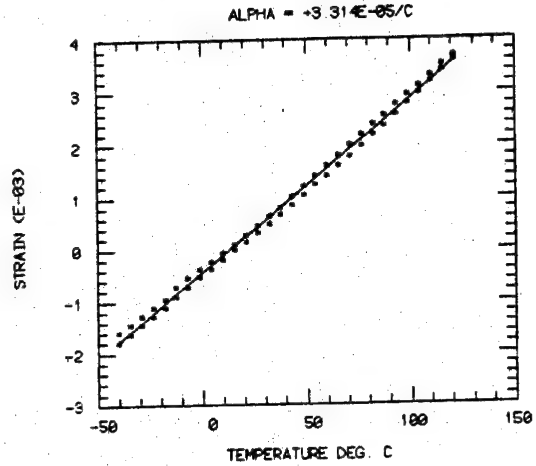

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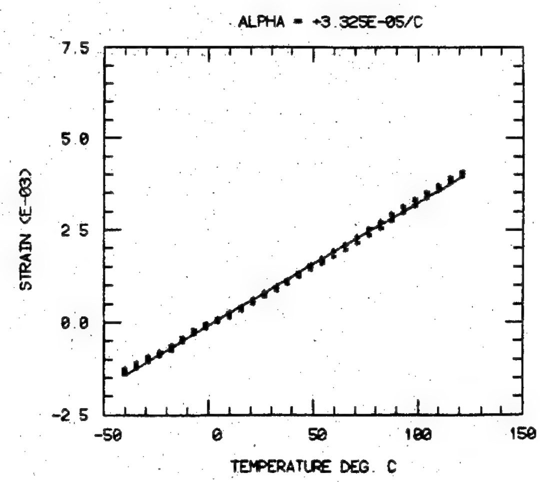

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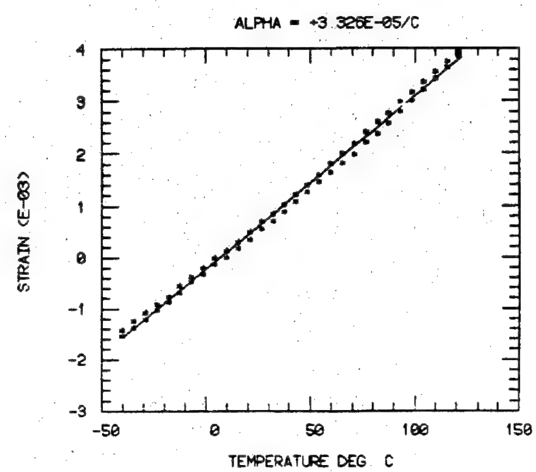

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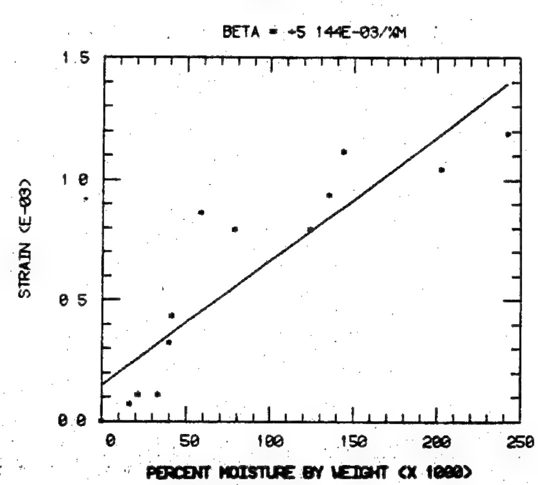

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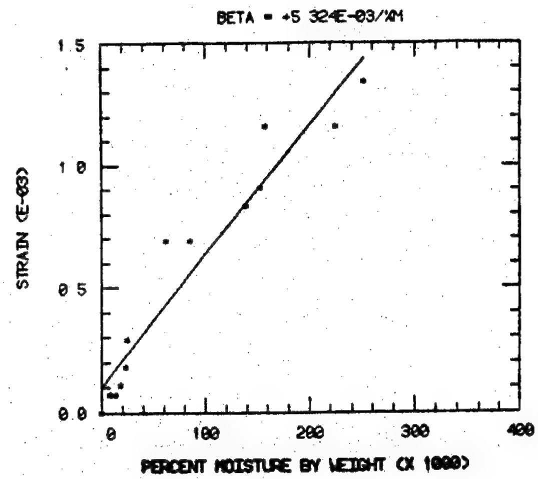

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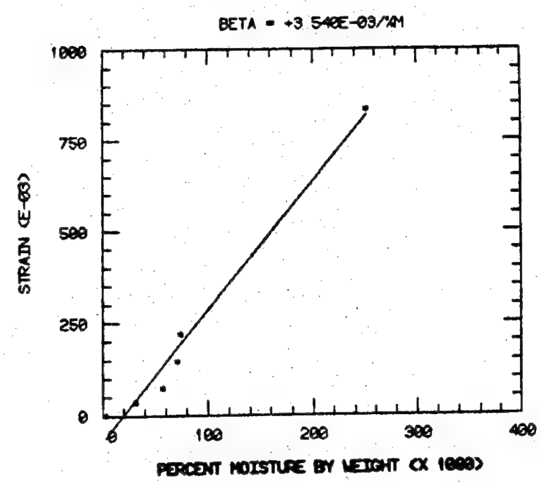

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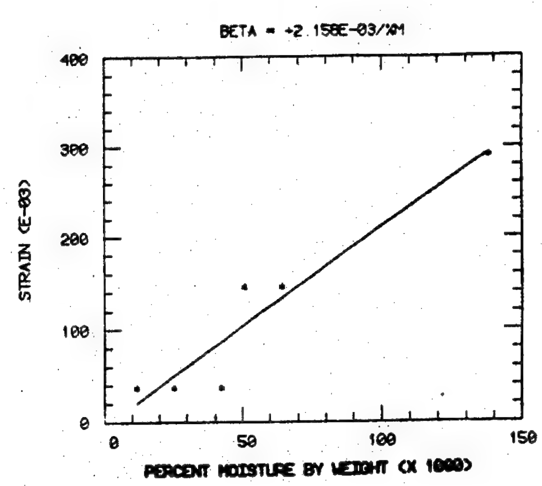

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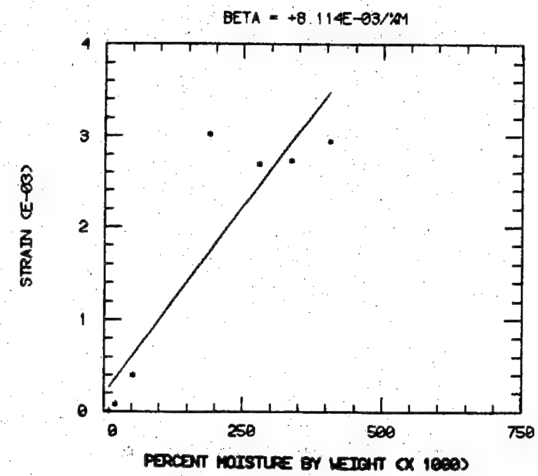

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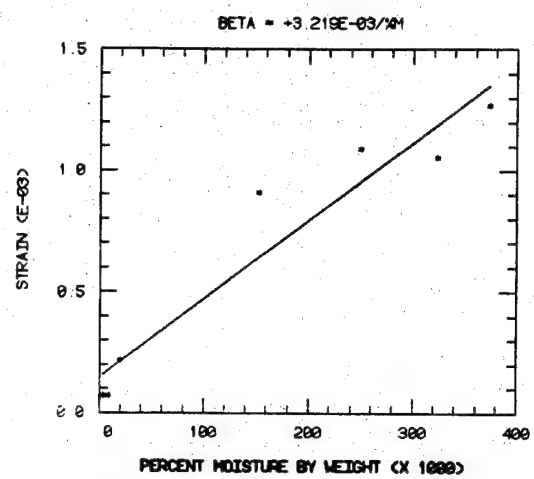

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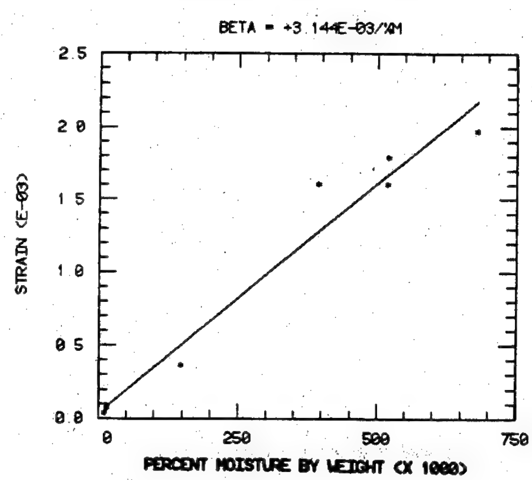

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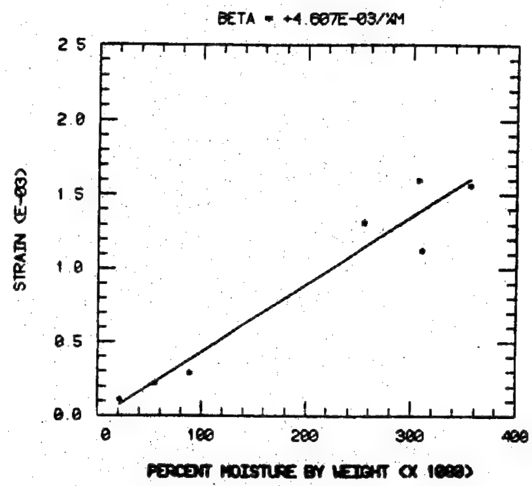

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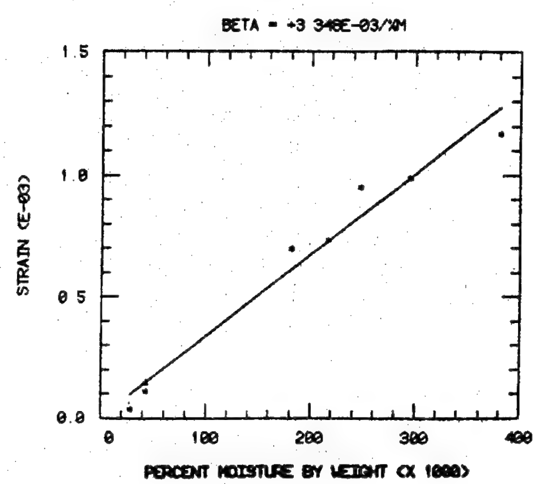

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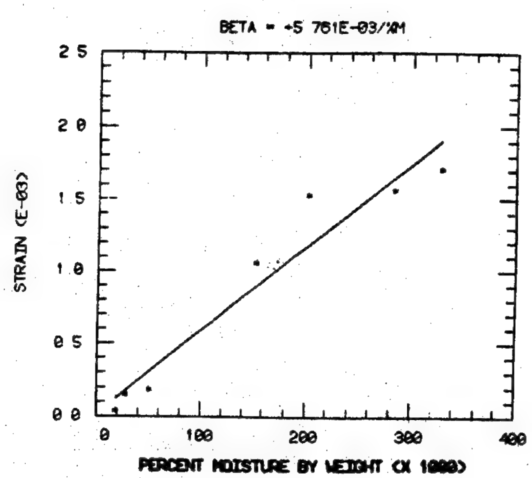

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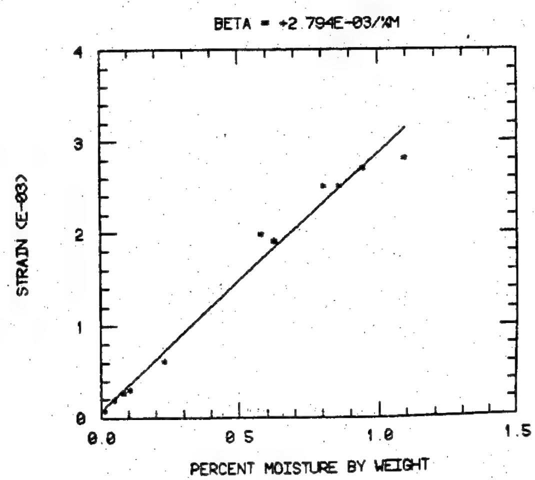

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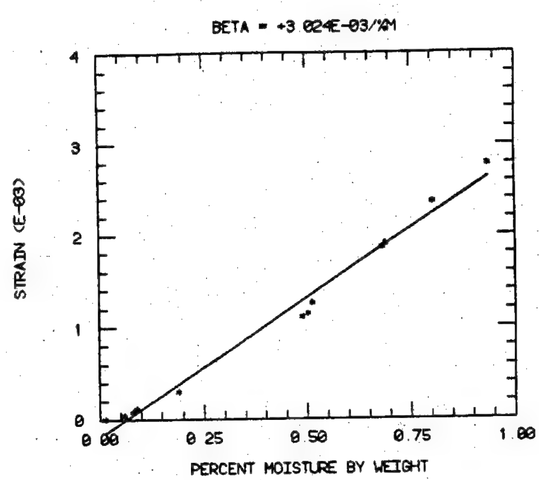

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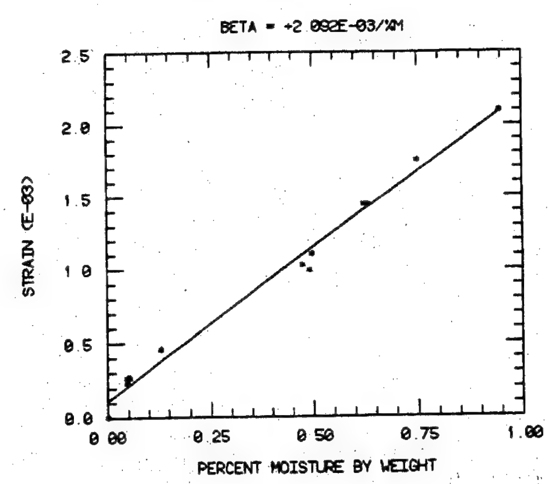

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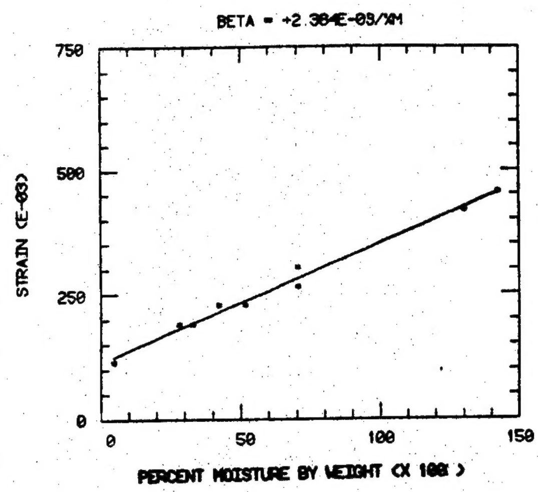

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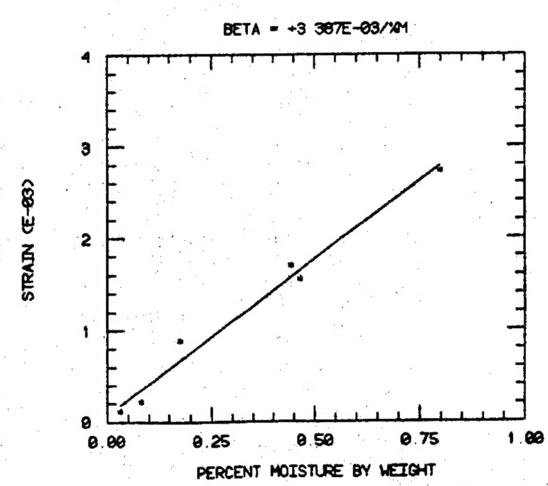

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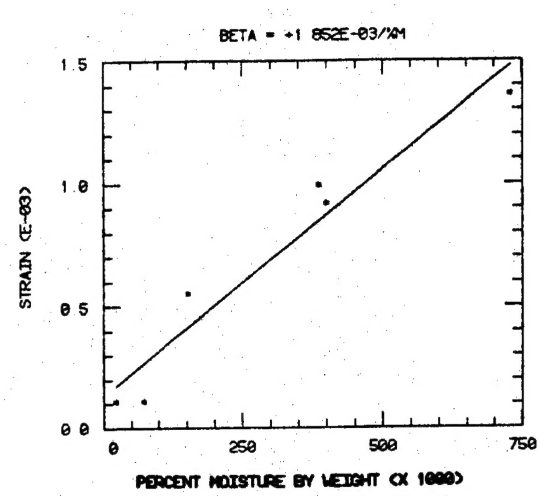

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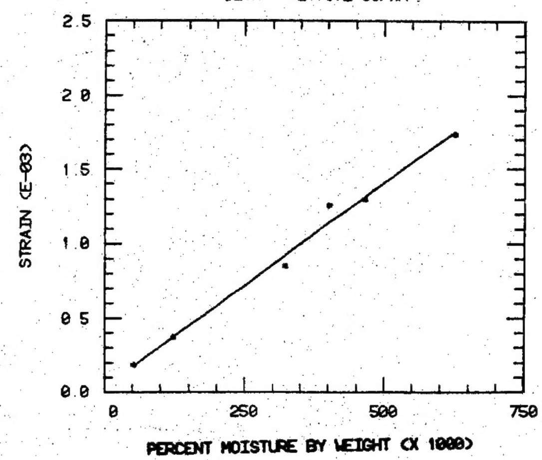

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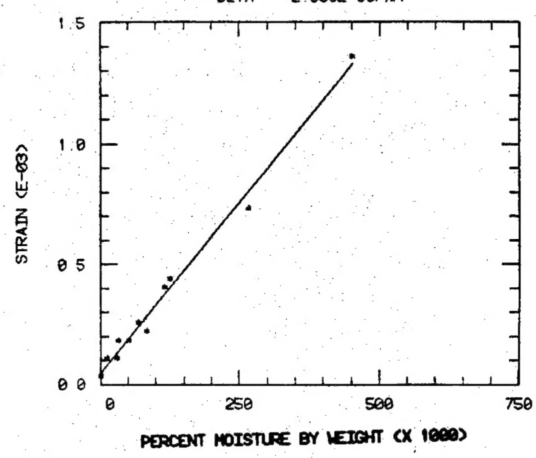

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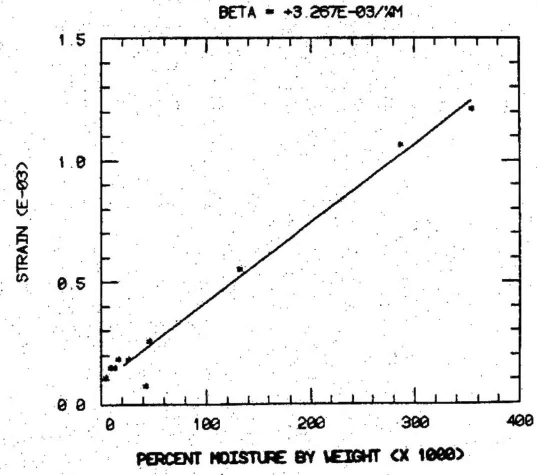

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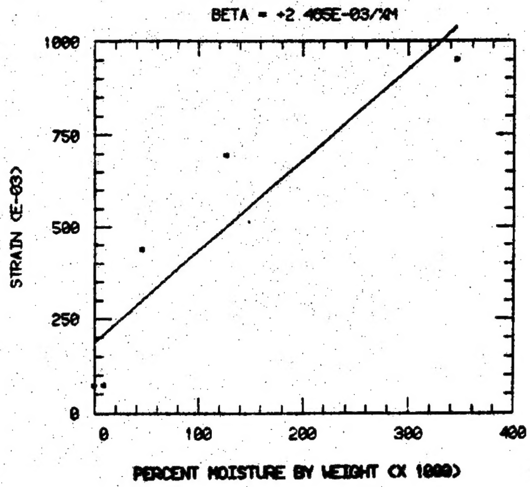

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16. Abstract

The mechanical properties of two neat resin systems for use in carbon fiber/epoxy composites were characterized. This included tensile and shear stiffnesses and strengths, coefficients of thermal and moisture expansion, and fracture toughness. Tests were conducted on specimens in the dry and moisture-saturated states, at temperatures of 23°C, 82°C, and 121°C. The neat resins tested were American Cyanamid 1806 and Union Carbide ERX-4901B(MPDA). Results were compared to previously tested neat resins.

Four unidirectional carbon fiber-reinforced composites were mechanically characterized. Axial and transverse tension and in-plane shear strengths and stiffnesses were measured, as well as transverse coefficients of thermal and moisture expansion. Tests were conducted on dry specimens only at 23°C and 100°C. The materials tested were AS4/3502, AS6/5245-C, T300/BP907, and C6000/1806 unidirectional composites.

Scanning electron microscopic examination of fracture surfaces was performed to permit the correlation of observed failure modes with the environmental test conditions.

17. Key Words (Suggested by Author(s)) polymer matrices; mechanical properties; carbon fiber-reinforced composites; failure surfaces		18. Distribution Statement Unclassified, Unlimited; Subject Category 24	
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